University of Alberta

Biology and Management of Field Violet (*Viola arvensis* Murr.) in Alberta

by

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Abstract

Field violet (*Viola arvensis* Murr.) is a pervasive weed of agricultural crops that has recently been identified in reduced-tillage fields in Alberta. Natural infestations of field violet were used to characterize its biology, evaluate its response to pre- (PRE) and post-crop emergence (POST) herbicides registered for use on spring wheat, conventional- and herbicide-tolerant canola, and quantify its in-crop competitiveness. Periods of peak emergence in early-June and September occurred in all experiments, and were generally associated with rainfall and low temperatures. Spring annuals dispersed mature seed in as few as 7 weeks after emergence, but persisted in a dormant state for up to 19 weeks under adverse conditions. Yield loss in wheat and canola due to field violet interference ranged from 0 to 7%. In wheat, only POST fluroxypyr + 2,4-D provided weed control. In canola, it was controlled by POST glyphosate (glyphosate-tolerant cultivar) and thifensulfuron-methyl (imidazolinone-tolerant cultivar). Application of PRE glyphosate (445 g ae ha^{-1}) was an effective control in wheat and glyphosate-tolerant canola. Field violet appears to be well adapted to growing conditions and farming practices in Alberta, but is poorly competitive and can be controlled by certain registered herbicides.

Dedication

This thesis is dedicated to my parents, Keith and Terry Lee Degenhardt, for their love, support and everything they have done and continue to do; to my brother, Kerry, for fond memories and teaching me individualism; to my sister, Heather, for keeping me grounded and making me laugh; and to my fiancé, Dani Xu, for supporting, assisting and loving me through every step of this project.

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List of Abbreviations / Acrononyms Used in Figures and Tables

BBCH,	scale that uses a universal number system to code the phenologically similar stages of development of all mono- and dicotyledonous plants.
Control,	visual estimate of percent field violet control
Cot,	cotyledon stage of development
DAE,	days after emergence
DAP,	days after planting
DAT,	days after treatment
DBE,	days before emergence
ED_{50},	effective herbicide dose necessary to cause a 50% reduction in weed weight
ED_{85},	effective herbicide dose necessary to cause a 85% reduction in weed weight
FALL,	post-harvest
GDD,	growing degree days
Int,	intercept
Lf,	leaf
Max,	maximum
Min,	minimum
POST,	post-crop emergence
PRE,	pre-planting
r,	Pearson correlation coefficient
R^2,	coefficient of determination *or* proportion of variation in dependent variable explained by the regression model
RU,	reproductive units
SE,	standard error of the difference between least square means (generally)
SEM,	standard error of the mean
v / v,	volume per volume
WAE,	weeks after emergence
WAP,	weeks after planting
WAT,	weeks after treatment

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Chapter 1

Literature review

1.1 Introduction

Field violet (*Viola arvensis* Murray) is native to Europe and is widespread throughout arable fields in that region (Hanf 1983; Wiersema and Leon 1999). Much of the literature published on this weed arises from research conducted in Europe. Studies have outlined the phytochemistry (i.e. Fraisse *et al.* 2001), habitat (i.e. Grundy *et al.* 1995; Wilson and Aebischer 1995), biology (i.e. Andreasen *et al.* 1991; Bachthaler *et al.* 1986), competitive ability (i.e. Ervio 1972; Fogelsfor 1977) and management (i.e. Lawrie *et al.* 1999; Salonen 1993) of field violet. Long-term research projects have enabled the development of models to predict plant population development (Gerowitt and Bodendorfer 2001) and describe both the agronomic and biological characteristics of these populations in Europe. Substantially less information is available on populations of field violet in other parts of the world.

Field violet has naturalized over large regions of the Americas and the continent of Australia (Alex and Switzer 1976; Bourdot *et al.* 1998; Requesens *et al.* 1997; Whitson *et al.* 1992). In field surveys in Argentina and New Zealand it was identified as the second and third most common weed, respectively (Requesens *et al.* 1997; Bourdot *et al.* 1998). In North America, it occurs in field and horticultural crops in 35 states and all 10 Canadian provinces (Doohan and Monaco 1992; USDA 2002). Aside from published research on the biology and management of the weed along the eastern seaboard (i.e. Ahrens 1988; Doohan *et al.* 1991; Doohan and Monaco 1992), and on management of the weed in phalaris (*Phalaris aquatica* L.) and cocksfoot (*Dactylis glomerata* L.) crops of Argentina (Bedmar *et al.* 1995, 1996), there is little information available on the naturalized biotypes of field violet in the Americas. There are no published reports of research conducted on field violet in western Canada.

This literature review will integrate published literature on the biology and management of field violet from around the world. The information will be divided into the following categories: taxonomy, morphology, similar species, ecology, phenology, phytochemistry, genetics, geographic distribution, economic importance, chemical management, cultural management and biological management. Information from all regions of the world will be amalgamated as research suggests intraspecific variation is primarily the result of environmental conditions and not the result of genetic differences between plants (Doohan and Monaco 1992; Kakes 1982).

This review will provide a framework to understand the dynamics of population development in western Canada.

1.2 Taxonomy

A member of the *Violaceae* family, *Viola arvensis* is one of 39 *Viola* species found in Canada (Scoggan 1978). Domestically, it is most commonly referred to as field violet in Canada (Alex *et al.* 1980; Doohan and Monaco 1992). Globally, it is referred to as European field pansy, field pansy, wild pansy, cultivated pansy, heart's ease and a number of non-English names (Ferron and Cayouette 1975; Hitchcock and Cronquist 1973; Muenscher 1955; Wiersema and Leon 1999). Due to its morphological similarities with *Viola tricolor* L., it has also been classed as *Viola tricolor* var. *arvensis*.

There are two subspecies of field violet: *Viola arvensis* Murr. subspecies *arvensis* and *Viola arvensis* Murr. subspecies *megalantha* Nauenburg (Espeut 1996). Subspecies *arvensis* is small flowered and mainly autogamous. Subspecies *megalantha* has a strong aroma and large, colorful corolla adapted for allogamic reproduction. It is thought to be an evolutionary predecessor of the *arvensis* subspecies (Nauenburg 1990). Subspecies *megalantha* is much less widely distributed and is found mainly in colline-montane vegetation zones of Europe (Espeut 1996, Nauenburg 1990).

1.3 Morphology

Field violet is a pansy. It has deeply divided, broad, foliaceous stipules and lateral petals pointing upwards, which distinguish it from other members of the *Violaceae* family (Doohan and Monaco 1992). The immature plant has a rosette of leaves and cotyledons that are 3 to 5 mm long, 3 to 4 mm wide and occur on long petioles (Stucky *et al.* 1994). The mature herb has a branched or unbranched, erect or prostrate, angular-terete stem (Appendix A, Figure A.1.1) that can reach as long as 30 cm and may have hairs on all surfaces or only on the angles (Gleason 1963). Leaves display dimorphism based on the position of their attachment to the stem. Both forms are petiolate, alternate, pubescent along the abaxial veins and have a serrated or scalloped edge. Lower leaves are acaulescent, oval to spatula-shaped, up to 1.5 cm long, up to 1.5 cm wide and have no stipules. Upper leaves are cauline, oblong to lanceolate, 2 to 8 cm long, 1 to 1.75 cm wide and have large, pinnately-lobed stipules at their axil (Appendix A, Figure A.1.1). The stipules are divided into 5 to 9 lobes, the terminal lobe being spatulate and almost as long as the main blade (Whitson *et al.* 1992). The blade-edge of the upper leaves is smoother than that of the lower leaves (Doohan *et al.* 1992). Roots are fibrous and, when crushed, emit a wintergreen odor (Radford *et al.* 1968).

Field violet has chasmogamous, perfect flowers, 1 to 1.5 cm long and up to 1 cm wide, composed of a corolla of five petals, which are shorter than or equal in length to the five sepals (Gleason and Cronquist 1991). The petals are generally cream-colored, but can have bluish-violet tips (Blamey and Grey-Wilson 1989). The lateral petals have a distinct black marking at the base and the lower petal has a noticeable yellow tinge at the throat. Flowers form at the leaf axils and are borne on slight pedicels, 2 to 4 cm in length. The corolla tube completely encloses the style and anthers. Anthers form inferior to the stigma (Doohan and Monaco 1992). The fruit is a ball-shaped capsule, 0.3 to 0.7 mm in diameter and 5 to 10 mm in length, with 1 cell and 3 valves. Seed are dark egg-yellow, obovate, 1.4 to 1.7 mm long, 0.7 to 0.8 mm wide (Appendix A, Figure A.1.2) and have a glossy, mucilaginous testa (Anderberg 1994).

1.4 Similar species

Viola tricolor and *V. bicolor* Pursh are both very similar in appearance to field violet. All three species are naturalized over much of the world, but only *V. tricolor* and field violet are found growing together with any regularity, due to their shared preferences for arable land in regions with moderate moisture and temperate conditions (Doohan *et al.* 1991). *Viola bicolor* thrives in temperate, non-wetland areas and is frequently found in dry fields and waste areas (Doohan and Monaco 1992; Gleason and Cronquist 1991). All three species can be distinguished by morphology and life cycle. Field violet has petals shorter than or equal in length to sepals (Appendix A, Figure A.1.3); *V. tricolor* has petals that are approximately 3 times the length of the sepals and *V. bicolor* has petals 2 times the length of the sepals. Both field violet and *V. tricolor* produce only chasmogamous flowers; *V. bicolor* produces chasmogamous flowers in early spring and cleistogamous flowers in late spring (Gleason and Cronquist 1991). *Viola tricolor* can be further differentiated by its brightly colored petals, which can be yellow, purple, violet-blue, or white, the upper petals generally being darker-colored than the lower ones (Gleason 1963).

1.5 Ecology and phenology

1.5.1 Life cycle

Field violet can exhibit either a summer annual or a winter annual life cycle (Gleason 1963; Alex and Switzer 1976). Doohan *et al.* (1991) reported that it is capable of germinating in spring, fall and winter, as long as temperatures are conducive for growth. Fall-germinating plants overwinter as a rosette or seedling, begin flowering in early spring and complete their life cycle in late autumn (Doohan and Monaco 1992). In temperate climates, plants that germinate in the spring can flower by late spring or early summer, completing their life cycle at the same time as the winter annual biotype. Observations of weeds persisting for up to 2 years in Ontario have led to the classification of field violet as a short-lived perennial (Alex and Switzer 1976).

1.5.2 Dormancy

The seedbank of field violet is very persistent. Viable seeds, believed to be 300 (Harrington 1972) and 460 years old (Odum 1965), have been exhumed from archaeological excavations. Gerowitt and Bodendorfer (2001) estimated seedbank depletion in a sugar beet (*Beta vulgaris* L.) – wheat (*Triticum aestivum* L.) – barley (*Hordeum vulgare* L.) rotation to be 19% per annum. In winter wheat plots tilled twice during the growing season, depletion was reported to occur at an annual rate of 36% (Wilson and Lawson 1992), slower than all other dicotyledonous weeds examined in the experiment [*Galium aparine* L., *Lamium purpureum* L., *Myosotis arvensis* (L.) Hill, *Veronica persica* Poir., *Veronica hederifolia* L.], except for *Papaver rhoeas* L., which had a statistically similar depletion rate. Over a 2-year study period, Froud-Williams *et al.* (1984) reported that germination of viable seeds was only 3% when surface-sown, and only 12% when seeds were evenly incorporated to a depth of 5 cm and soil was stirred at monthly intervals. Wilson and Aebischer (1995) reported that only 1% of viable seeds within a 20 cm soil core germinated in a single year. Field violet seeds buried for five years in earthenware cylinders at depths of 2.5, 7.5 and 15 cm remained viable at rates of 6, 7 and 8% of initial seeds, respectively, in tilled cylinders and 12, 23 and 44%, respectively, in undisturbed cylinders (Roberts and Feast 1972). Seedbank longevity has been attributed to extended seed dormancy (Doohan *et al.* 1991; Doohan and Monaco 1992; Wilson and Lawson 1992).

Baskin and Baskin (1995) conducted extensive research on dormancy of mature field violet seeds harvested in late spring from the University of Kentucky research farm (38 °N, 84.5 °W). Collected seeds were buried in pots and placed in a glasshouse maintained at seasonal temperatures. Seeds were exhumed every month and tested for germination in light and darkness in incubators adjusted to diurnally fluctuating temperature regimes of 15/6, 20/10, 25/15, 30/15 and 35/20 °C with a 12/12 hour daily thermoperiod. Seeds from the first year of collection were observed to be dormant from the time of maturity until fall, at which time they entered a nondormant state that lasted until January when the average minimum temperature was below 0 °C. Nondormancy returned in June when the average minimum temperature was 15 °C. This annual dormancy:nondormancy cycle, following the breakage of primary dormancy, is indicative of an obligate winter annual (Baskin and Baskin 1983, 1990). Seeds harvested in the spring of the second year became nondormant shortly after maturity (Baskin and Baskin 1995). These seeds entered conditional dormancy in the winter months, where germination occurred only at ambient temperatures, but returned to a nondormant state in the fall. This cycle of annual conditional dormancy:nondormancy has led to the classification of field violet as a facultative winter annual (Baskin and Baskin 1981, 2001). To date, field violet is the first weed species reported to produce seedlots with either annual dormancy:nondormancy or annual conditional dormancy:nondormancy cycles (Baskin and Baskin 2001). This unique attribute allows field violet to germinate year-round under suitable climatic conditions.

A period of warm stratification and a large diurnal fluctuation in temperature are requirements for breaking dormancy. Froud-Williams *et al.* (1984), Hakansson (1983) and Baskin and Baskin (1995) reported that germination of field violet seeds buried under natural conditions in the UK (51 °N, 1 °W), Sweden (59 °N, 17 °E) and the United States (38 °N, 84 °W) was greatest from early autumn to spring, following a period of hot weather. Doohan *et al.* (1991) germinated seeds at 6 temperature regimes (5/5, 15/15, 15/5, 20, 25/15 and 25 °C) with a 8/16 hour thermoperiod and found that the greatest germination occurred when temperatures fluctuated diurnally (15/5 and 25/15 °C). Baskin and Baskin (1995) tested germination of seeds stored in soil for 4 months in incubators set on 12/12 hour thermoperiods, maintaining 6 temperature regimes (5/5, 15/6, 20/10, 25/15, 20/15 and 35/20 °C). Seeds kept at a diurnal maximum of at least 25 °C had almost 100% germination under all thermoperiods tested. Those stored at 15/6 and 20/10 °C could germinate at low, but not high, temperatures. Seeds kept at 5 °C were not capable of germinating. Baskin and Baskin (2001) suggested that, as facultative winter annuals lose dormancy, they first gain the capacity to germinate at low temperatures, and only gain the ability to germinate at high temperatures following the complete loss of dormancy.

Cold temperatures can induce the onset of secondary dormancy or conditional dormancy. Nondormant seeds kept at 5 °C for 12 weeks did not germinate under any thermoperiod tested (Baskin and Baskin 1995). Two separate seedlots, incubated at 30/15 °C with a 12/12 hour thermoperiod for 12 weeks, and thereafter moved to 5 °C for 12 weeks, entered conditional dormancy at rates of 100% and 33%. Doohan *et al.* (1991) kept seeds from North Carolina at 1 °C for 10 months and found that 40% entered into conditional dormancy. The same research group found that 90% of seeds from Nova Scotia, stored for 6 months at 22 °C then 2–3 months at 1 °C, were induced to enter secondary dormancy.

Dormant seeds could not be stimulated to germinate by any of the following treatments: imbibition of seeds in tap water, sulfuric acid scarification for 2 minutes followed by imbibition in tap water, imbibition in 10^{-4} M kinetin, or sulfuric acid scarification followed by imbibition in 10^{-4} M kinetin (Doohan and Monaco 1992). Dormancy in some field violet seeds can be broken by short exposure to anaerobic, or near-anaerobic conditions. Lonchamp and Gora (1979) noted increased germination of field violet seeds placed in oxygen partial pressures of 0, 2 and 4% for five days and then returned to atmospheric pressure. If they extended the period of incubation under low oxygen partial pressure to 25 days, the seeds germinated at the same rate as those kept at continuous atmospheric pressure. Acid scarification, followed by imbibition with 10^{-7} M giberrelic acid (GA_3), or imibibition in 10^{-3} M GA_3 only, has also been shown to break dormancy resulting in high rates of germination (Doohan *et al.* 1992).

Baskin and Baskin (1995) reported a maternal influence on the response of seed dormancy to moisture. If rainfall was greater than 5 cm in the 2 weeks preceding seed collection, germination the following spring was in the range of 35 to 100%. If rainfall was less than 5 cm, germination was less than 10%. They suggest that seeds maturing in an environment with high moisture and temperature become conditionally dormant in the following spring and those maturing at low temperatures and high rainfall or high temperatures and low rainfall are dormant the following spring.

There have been two contrasting reports on the influence of light on dormancy of field violet seeds. Baskin and Baskin (1995) studied germination of buried seeds in light (14 hour photoperiod with white fluorescent light generating 20 μmol m^{-2} s^{-1}, 400–700 nm) and continuous darkness. In light, germination of nondormant seeds was near 100%. In darkness, exhumed seeds with an annual dormancy : nondormancy cycle germinated to a maximum of 20% after 17 months of burial under natural conditions and to a maximum of 90% after 29 months. Seeds with an annual conditional dormancy : nondormancy cycle germinated to maximums of 60 and 40% after 7 and 15 months of burial, respectively. These authors thereafter classified the weed as being capable of germinating to a higher percentage in light than in darkness (Baskin and Baskin 2001). Doohan *et al.* (1991) observed the opposite effect. Seeds stored for 6 months in brown paper bags at 22 °C, followed by 3 months of storage in transparent glass vials at 1 °C, germinated to a maximum of 1% in light (24 hour photoperiod with white fluorescent light generating 100 μmol m^{-2} s^{-1}, 400–700 nm light). Those in continuous darkness, checked with a green-safe light (3.2 μmol m^{-2} s^{-1}, 500–600 nm), had a maximum of 90% germination. Interestingly, they also found that dormancy of seeds could not be broken by continuous irradiation with red light. Seeds that germinate well in the dark often remain dormant when exposed to far-red light, but exit dormancy when exposed to red light (Baskin and Baskin 1985; Botha *et al.* 1982). The authors could not explain this result. Literature published on seed dormancy suggests possible explanations for both the observed stimulatory effect of darkness and the observed inhibitory effect of light. Continuous exposure to light, particularly of a high irradiance, can inhibit seed germination (Roberts *et al.* 1987). Perhaps the continuous exposure to light exceeded the maximum photon dose that the field violet seeds could intercept in a given period of time without inhibiting germination (Ellis *et al.* 1986a, 1996b). The increased germination observed in darkness might be explained by studies reporting that some species require only a very small amount of light to break dormancy, which in rare cases, can be fulfilled by the irradiance from a green safe-light (Isikawa 1952; Baskin and Baskin 1975, 1979, 2001). Alternately, the differences could simply be a reflection of inherent differences between seed from two distinct populations.

1.5.3 Germination

Optimal conditions for germination of nondormant field violet seeds include: soil temperatures above 5 °C and below 20 to 30 °C (Doohan *et al.* 1991; Baskin and Baskin 1995), large diurnal fluctuations in temperature (Doohan *et al.* 1991), high soil organic matter and low soil clay content (Walter *et al.* 2002), oscillation between anaerobic or near-anaerobic conditions and normal atmospheric conditions (Lonchamp and Gora 1979), and non-continuous exposure to irradiance with a wavelength of 400–700 nm accumulating to less than 100 μmol m^{-2} s^{-1}. Threshold water potentials have not been established, but reports of drought tolerance indicate that field violet has low osmotic thresholds or requires little accumulated hydrotime to germinate (Bachthaler 1986; Bradford 2002; Gummerson 1986). Germination is also stimulated by tillage (Chancellor 1964; Doohan *et al.* 1991).

1.5.4 Emergence

Patterns of emergence follow an annual pattern of periodicity dependent on the environment and inherent dormancy of seeds. Weeds emerged in fall and spring in the UK (Roberts and Feast 1972), Sweden (Hakansson 1983) and Nova Scotia (Doohan *et al.* 1991) and from fall until spring in North Carolina (Doohan *et al.* 1991). In Finland (60 °N, 23 °E), peaks of emergence occurred in mid-June and mid-July, but no fall counts were conducted in that study (Ervio 1981). Regression analysis was used to determine relationships between weed flushes and climatic parameters two weeks prior to peak emergence. Peak emergence in early summer was reported to be related to the sum of daily maximum temperatures (Ervio 1981). In mid-summer, peak emergence was related to cumulative daily rainfall, maximum temperatures and the difference between maximum and minimum temperatures. A negative regression was observed between emergence and cumulative minimum temperature.

Field violet emergence is greater in years following inputs to the seedbank. Wilson and Lawson (1992) counted weeds arising from a single year of fall seeding field violet. They found that emergence was significantly greater the year following seeding, but peaked 2 or three years after initial seed incorporation. Emergence has been positively correlated with soil organic matter and negatively correlated with clay content (Andreasen *et al.* 1991; Walter *et al.* 2002). Light textured, sandy soil is more conducive to weed emergence than heavier-textured soils, although greater emergence has been observed in the latter type of soil when moisture is limiting (Bachthaler *et al.* 1986). Nordmeyer and Dunker (1999) reported that high soil pH is restrictive to field violet emergence, however other studies have reported greater emergence in neutral or slightly basic soils (Clausen 1922; Bachthaler *et al.* 1986). Moisture is required for weed emergence and irrigation has been observed to stimulate emergence and increase weed density (Bachthaler *et al.* 1986).

Field violet has a shallow depth of recruitment and has been shown to emerge from a maximum depth of 20 mm and optimally at depths of 5 to 15 mm (Chancellor 1964; Froud-Williams *et al.* 1984). Over a 5-year study, Roberts and Feast (1972) observed 60% emergence from seeds evenly distributed within soil to a maximum depth of 25 mm, while emergence from seeds distributed to a maximum depth of 150 mm was only 15%. Tillage results in increased emergence of buried seeds. In the UK, emergence of plants from seed sown to a depth of 75 mm in early October and tilled in June was five times greater than emergence from seed left untilled on the soil surface (Froud-Williams *et al.* 1984). In Nova Scotia, tilled plots had more emergence than untilled plots in June, July, October and November (Doohan *et al.* 1991). Weed emergence did not differ between treatments in May, August or September.

Competition from other species has been shown to cause a reduction in field violet emergence. Mukula *et al.* (1969) reported that the density of field violet was inversely proportional to the total number of weeds. Density increased when competition was reduced by drought (Bachthaler *et al.* 1986). Ervio (1981) found field violet composed the greatest proportion of emerged weeds in spring cereals over sugar beet or unsown land. However, the sugar beet and unsown plots had substantially more total weeds than the spring cereal plots, suggesting that competition between weed species is a limiting factor for field violet emergence.

1.5.5 Growth and flowering

Field violet is indeterminate, initiating flowering in spring and continuing to grow both vegetatively and reproductively until temperatures fall below 0 °C for an extended period of time (Doohan and Monaco 1992). New flowers are often observed on senescing plants.

Growth is limited by interspecific competition. Density decreases with increasing populations of competitors (Bachthaler *et al.* 1986; Mukula *et al.* 1969). In field surveys in the UK, field violet density has been shown to increase with distance from the field edge (Marshall 1989; Wilson and Aebischer 1995). Low density on the field perimeter was associated with greater species diversity and increased competition with other weed species. Semb (1996a, 1996b) studied the competitive ability of field violet, barley and four other weeds species [*Brassica rapa* L., *Chenopodium album* L., *Galeopsis tetrahit* L. and *Stellaria media* (L.) Vill.] by measuring the effects of irradiance and temperature on plant growth parameters. At optimal irradiance (~200 μmol m^{-2} s^{-1}) and optimal temperature (20/14 °C with a 17/7 hour thermoperiod), field violet had the shortest stem and the least amount of dry matter and total leaf area of all six species. At low light intensity (<150 μmol m^{-2} s^{-1}), field violet had a low net assimilation rate (dry weight accumulation over time), but compensated by increasing its leaf area ratio (leaf area : dry weight). At high light intensity, the leaf area ratio was low, but the net assimilation rate was high. These trends were also observed in field experiments (Semb 1996c). It was suggested that the only competitive advantage of field violet is a high shoot to root ratio and a relative growth rate that is approximately the same at all light intensities, making it well adapted to variation in light intensity.

Optimum irradiance for dry matter accumulation has been reported to be 53% of full sunlight, indicating a tolerance for shade (Doohan and Monaco 1992; Fogelfors 1973). In growth chamber studies, maximum dry matter has been obtained at as low as 180 μmol m^{-2} s^{-1} (~10% full sunlight) (Semb 1996a). Increasing irradiance from 100 to 400 μmol m^{-2} s^{-1} stimulated increased flowering, leaf area, and shoot dry weight (Semb 1996b). Flowering was also stimulated by increasing temperature up to 30/21 °C with a 17/7 hour thermoperiod. However leaf area and shoot dry weight did not increase when temperature was raised beyond 20/14 °C (Semb 1996b). A 20/14 °C diurnal temperature fluctuation was also shown to confer the highest photosynthetic rate. Moist conditions are preferable for vegetative and reproductive growth, so long as competition from other species is limited (Bachthaler *et al.* 1986). Nutrient requirements for the growth of field violet have not been established (Bachthaler *et al.* 1986), however Walter *et al.* (2002) found that density was positively correlated to organic matter in two out of six site-years and negatively correlated with K in one of six site-years. A reduction in field violet density in response to a high concentration of exchangeable K was also observed in a Danish study that sampled 316 fields over three years (Andreasen *et al.* 1991). Application of nitrogen at 160 kg N ha^{-1} resulted in greater plant weight than at 40 kg N ha^{-1} (Grundy *et al.* 1995).

1.5.6 Seed set

Doohan and Monaco (1992) observed the growth of field violet in a greenhouse in Nova Scotia during June and July (24/18 °C thermoperiod with a natural photoperiod). Flower buds formed approximately 4 weeks after germination. At high temperature and irradiance (30/21 °C thermoperiod with a 17/7 hour photoperiod at an intensity of 294 $\mu mol\ m^{-2}\ s^{-1}$) generative structures were observed on some plants in as early as 14 days after planting (Semb, 1996b). Capsule production is linearly related to plant height and both are increased by N fertilization (Gerowitt and Bodendorfer 1998). Seed capsules produce between 25 and 80 seeds (Gerowitt and Bodendorfer 1998; Korsmo 1930) and plants have been estimated to produce between 270 (Gerowitt and Bodendorfer 1998) and 2500 (Bachthaler *et al.* 1986) seeds annually, in-crop. Under optimal conditions in growth chambers, estimated seed production during a 6-month period was 20,000 to 46,000 seeds from a single plant (Doohan and Monaco 1992). Gerowitt and Bodendorfer (1998) reported that 63–74% of seeds directly harvested from plants grown in the field are viable.

1.5.7 Seed dispersal

Newly formed pods arise on concave pedicels and face the ground. At seed maturity, the pedicels become convex and fruit dehisce, exposing three valves bearing seeds (Appendix A, Figure A.1.4). As the fruit continues to dry, valves fold inwards and seeds are expelled. Seed can be propelled up to 2.1 m from the host plant (Salisbury 1964). Additional dispersal occurs by wind and surface water (Doohan and Monaco 1992). The mucilaginous seed coat allows for secondary dispersal by foraging animals and farm equipment.

In North America, field violet has been classed as a garden escape (Muenscher 1955) and initial field dissemination has been credited to the spreading of garden compost contaminated with field violet seed (Welsh *et al.* 1987). In strawberries (*Fragaria spp.*), it is proposed that contaminated fields are the result of transplanting infested strawberry bundles and spreading grain straw containing field violet seeds (Ahrens 1988; Chase and Putnam 1984).

1.6 Phytochemistry

Aerial parts of field violet contain mucilage (17–22%), ash (10.6–14.8%), K (2.8%), salicylic acid (0.1%) and flavonoids (1.6–2.9%) consisting of rutin (0.6–1.2%), violanthin (0.8%) and violarvensin (0.2–0.8%) (Fraisse *et al.* 2001). Novel fractionation protocols have resulted in the discovery of several new polypeptides contained within the aerial portions of the plant (Goransson *et al.* 1999). The primary root contains methyl salicylate that is released from special secretory cells located within the endodermis (Hayden and Clough 1990). This compound produces the wintergreen aroma observed when roots are crushed, and may provide protection from predation by soil-borne pathogens (Hayden and Clough 1990; Singleton and Kratzer 1973).

1.7 Genetics

Field violet is a diploid species with a haploid chromosome number of n = 17 (Moss and Packer 1983; Radford *et al.* 1968; Tutin *et al.* 1968). Pollen microspores are heteromorphic, having either 4 or 5 apertures (Mignot *et al.* 1995). Fertilization is primarily autogamic although some degree of allogamy does occur (Salisbury 1964). Hybridization with other *Viola* species, such as *V. tricolor (2n = 26)*, is probable (Blamey and Grey-Wilson 1989; Clausen 1922; Tutin *et al.* 1968).

1.8 Geographic distribution

Field violet is endemic to many regions and has been reported in Africa, including: Canary Islands (Spain), Madeira Islands (Portugal), Morocco, Algeria and Tunisia; temperate Western Asia including: Cyprus and Turkey, Russian Siberia; and Europe including: Albania, Austria, Belarus, Belgium, Bulgaria, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy (including Sardinia and Sicily), Latvia, Lithuania, Moldova, Netherlands, Norway, Poland, Portugal, Romania, Russian Europe, Spain, Sweden, Switzerland, Ukraine (including Krym), United Kingdom and Yugoslavia (Wiersema and Leon 1999). It has naturalized elsewhere.

Field violet may have been introduced to North America by European settlers who planted it for culinary and medicinal purposes (Doohan and Monaco 1992). Whitson *et al.* (1992) reports that it "escaped from cultivation to become an occasional problem". Field violet has been identified in most grain producing countries of the northern hemisphere, ranging from a northern latitude of 60 °N in Finland to a southern latitude of 30 °N in the USA (Ervio 1981; USDA 2002). It occurs in agricultural regions of the southern hemisphere including New Zealand (44

°S, 171 °E) and Argentina (36 °S, 53 °W) (Bourdot *et al.* 1998; Requesens *et al.* 1997). It inhabits field crops in all 10 provinces of Canada and 35 states of the USA (Doohan and Monaco 1992; USDA 2002). In Canada, it is most frequent in Ontario, Québec, New Brunswick, Nova Scotia, Newfoundland and British Columbia. In surveys in New Brunswick (Doohan 1985) and the L'Assomption and Richelieu regions of Québec (Doyon *et al.* 1986a; 1986b), field violet was observed in 19 and 10%, respectively, of cereal fields. It has been observed in Alberta in the weed survey conducted in 1997 (Thomas *et al.* 1998), but was not identified in the most recent weed survey of Alberta (Leeson *et al.* 2002).

1.9 Economic importance

1.9.1 Negative economic impacts

Field violet is a weed of crops, disturbed and undisturbed areas (Gleason and Cronquist 1991; Whitson 1991; Wiersema and Leon 1999). It is abundant in cereal grain fields as they provide an environment favorable for vegetative growth, seed set and seed dispersal (Doohan *et al.* 1991; Fourbet *et al.* 1979). Bachthaler *et al.* (1986) reported that the frequency of field violet on arable land in Germany has increased during the last few decades and they credited this increase to reduced utilization of rotational crops in cereal crop production and to an increased reliance on chemical weed management. Field violet is one of the most prevalent weeds in cereal crops of Europe – identified as the third most common weed in winter cereals and the seventh most common weed in spring cereals (Schroeder *et al.* 1993). Holm *et al.* (1979) reported it as being widespread in grain crops of the UK, Finland, Portugal and the former Soviet Union. It is the largest weed problem of winter rapeseed (*Brassica napus* L.) producers in West Germany, where it is also a concern in sugar beet, sweet turnip (*Brassica rapa*), maize (*Zea mays* L.) and forage crops (Bachthaler *et al.* 1986). Field violet was found in 70% of wheat and barley fields surveyed in Canterbury, New Zealand over a 4-year period (Bourdot *et al.* 1998). In Canada and the USA there have been limited reports, predominantly from the eastern states and provinces, of infestations in cereal, oilseed, pulse, fruit, vegetable and ornamental crops (Doohan and Monaco 1992; Doohan *et al.* 1993).

As a result of its depth of recruitment and growth habit, field violet is not considered to be a strong competitor with cereals (Semb 1996a, 1996b, 1996c). In research conducted at Bristol, UK, cereal yields were reduced by only 2% at a weed density of 109 plants m^{-2} (Wilson 1989). Field violet competes by forming a dense mat of stems that interferes with row crop establishment and management practices (Doohan *et al.* 1992). Fogelfors (1977) calculated yield loss of barley resulting from competition with field violet, and derived the following formula from regression analysis: Yield (kg ha^{-1}) = 4226.75 – 1.022 * 10^{-3} N_v ($r = -0.93$; $P<0.001$), where N_v = number of field violet plants per hectare. Using this formula, at a weed density of 50 plants m^{-2}, barley yield would be reduced by 12%. Yield losses increased with decreasing crop density. In winter wheat, field violet reduced yield by 9 and 14% at densities of 167 and 500 seedlings m^{-2}, respectively (Wilson *et al.* 1995). Winter barley yields decreased with a weed density of greater than 50 plants m^{-2} (Miklaszewska *et al.* 1996). Severe infestations in strawberry fields have resulted in crop abandonment (Ahrens 1988). Field violet is less competitive with spring-sown cereals (Raatikainen *et al.* 1978; Froud-Williams *et al.* 1983). In Sweden, yield loss of spring sown wheat and barley due to interference from a natural weed community was reportedly negligibly affected by field violet, even though it was the third most frequent weed (67% of quadrats, n = 1586) and occurred at an average density of 33 plants m^{-2} in weed counts conducted within 7 weeks of crop sowing (Bostrom *et al.* 2003). Yield loss information in spring sown cereals and oilseeds in Canada is not available.

Seeds of field violet can be harvested with grain crops. Bourdot *et al.* (1998) observed that field violet was the fifth most frequent weed above 15 cm (harvest height) at crop maturity in winter wheat. In winter barley, an average of 30 field violet seeds per square meter of crop were detected in grain samples collected with a plot harvester (Gerowitt and Bodendorfer 1998). Bachthaler *et al.* (1986) reported that above ground plant tissues from field violet can block sieve holes of mechanical harvesters and result in an increased moisture content of harvested grain.

Field violet is an alternate host of *Mycocentrospora acerina* (Hartig) Deighton, the causal agent of liquorice rot of carrot (*Daucus carota* L.) (Hermansen 1992). This disease is economically significant to carrot producers in many temperate regions of Europe, North America, Australia and New Zealand (Sutton and Gibson 1977). Infection of field violet by *M. acerina* reduces the effectiveness of crop rotation to non-host species and increases the amount of disease inoculum within the soil (Hermansen 1992). Field violet can also act as a disease reservoir for beet mild yellowing luteovirus (BMYV) and beet western yellow luteovirus (BWYV), the causal agents of yellowing of sugar beet in the UK and western USA, respectively (Duffus *et al.* 1961; Smith and Hallsworth 1990; Stevens *et al.* 1994). In controlled experiments, aphids (*Myzus persicae* (Sulzer, 1776)) feeding on field violet transferred BMYV to sugar beet and BWYV to rapeseed (Stevens *et al.* 1994).

1.9.2 Beneficial uses and properties

Chemical constituents of field violet have resulted in its use as an expectorant, diuretic and antiinflamatory (Tutin *et al.* 1968). Some recently discovered compounds are believed to be uteroactive (Gran *et al.* 2000) and others reportedly have haemolytic properties (Schopke *et al.* 1993). All species within the *Viola* genus are edible (MacLeod and MacDonald 1988). Both flowers and leaves are high in vitamin A and C and leaves have been reported to have a positive effect on the digestive system. The leaves of field violet have been used fresh in salads and as thickeners in soup (le Strange 1977).

1.10 Chemical Management

1.10.1 Control in cereals and grasses

In Europe, the most consistent chemical control has been achieved with Group 2 (Mallory-Smith and Retzinger 2003) herbicides (Doohan and Monaco 1992; Roberts and Bond 1983, 1984). Metsulfuron applied at 4 and 6 g ai ha^{-1} controlled seedling field violet in winter wheat and spring barley, respectively (Christie and Cornwell 1984; Davies and Wilson 1997). Tribenuron and triasulfuron gave an acceptable reduction in field violet growth at a rate of 7.5 g ai ha^{-1} (Davies and Wilson 1997). Applied pre-crop emergence (PRE), amidosulfuron (15 g ai ha^{-1}) controlled field violet in wheat. Herbicide evaluations in phalaris (*Phalaris aquatica*) and cocksfoot (*Dactylis glomerata*) crops in Argentina, indicated that adequate control, one month after application, was obtained with treatments containing the sulfonylureas, metsulfuron or triasulfuron (Bedmar *et al.* 1995, 1996). However, three months after application, only metsulfuron + dicamba (4 + 48 g ai ha^{-1}) and triasulfuron + terbutryn + dicamba (4 + 120 + 48 g ai ha^{-1}) provided acceptable control.

Pendimethalin (Group 3), diflufenican (Group 12) and isoproturon (Group 7) are effective herbicides for field violet in winter cereals (Adamczewski *et al.* 1998; Cramp *et al.* 1987; Jenneus 1983; Miklaszewska *et al.* 1996). In laboratory studies, uptake of soil-incorporated diflufenican by field violet was 24-fold greater than uptake by wheat, and 4-fold greater than *G. aparine* (Haynes and Kirkwood 1992). Chlorphyll content was reduced by 50% at a concentration of 1.5 mM, compared to 0% in wheat and 25% in *G. aparine*.

Herbicide mixtures are often more effective than products applied alone. Grundy *et al.* (1995) showed that clopyralid (56 g ai ha^{-1}) + fluroxypyr (180 g ai ha^{-1}) + ioxynil (180 g ai ha^{-1}) reduced biomass, the number of capsules per plant and the number of seeds per capsule by 50, 50 and

10%, respectively. At one quarter rate, the same variables were reduced by 40, 25 and 7%, respectively. Field violet was controlled in experiments in Germany with isoproturon + ioxynil + mecoprop, isoproturon + bifenox + bromoxynil, metsulfuron methyl + thifensulfuron and isoproturon + bifenox + fluroxypyr in wheat, and with isoproturon + ioxynil + mecoprop, isoproturon + bromoxynil + metsulfuron methyl and isoproturon + bifenox + fluroxypyr in barley (Gerowitt and Bodendorfer 1998). Linuron + bifenox (Lake 1974), mecoprop + tribunil (Jenneus 1983), MCPA + dichlorprop-P, MCPA + mecoprop-P (Salonen 1993), terbutryn + triasulfuron (Dovydaitis 1997) and florasulam + liquid ammonium nitrate urea (Becker *et al.* 2000) have also provided acceptable control in winter cereals. MCPA + fluroxypyr (400 + 100 g ai ha^{-1}) reduced weed density and dry biomass by close to 90% in spring barley, but only suppressed weed growth in spring wheat (Salonen 1993).

1.10.2 Control in oilseeds

Pre-plant incorporated (PPI) Group 3 products have been used successfully to control field violet. Trifluralin, when applied in combination with PRE metazachlor, gave moderate control in winter rapeseed (Gummeson 1983). In winter flax (*Linum usitatissimum* L.), trifluralin at 420 and 840 g ai ha^{-1} gave some degree of control (Froment and Turley 1998b).

1.10.3 Control in fruit and vegetable crops

In strawberries, field violet can be controlled with PRE application of terbacil (0.5 kg ai ha^{-1}), DCPA (11 kg ai ha^{-1}) or oxyfluorfen (0.25 kg ai ha^{-1}). Applied post-crop emergence (POST), the Group 14 products oxyfluorfen (0.6 kg ai ha^{-1}) and aciflurofen (1.1 kg ai ha^{-1}) reduced growth of field violet over-wintering rosettes by 80 and 100% (Doohan *et al.* 1993). Pre-plant incorporated metolachlor (2.64 kg ai ha^{-1}) and pendimethalin (1.68 kg ai ha^{-1}) applied POST or PPI, reduced weed stand by greater than 90% in transplanted strawberries [Canadian Agricultural Services Coordinating Committee (CASCC) 1997]. No field violet plants survived directed spot applications of phenmedipham, paraquat or paraquat + diquat. Roberts and Bond (1983) reported that pyridate (2 kg ai ha^{-1}) was effective for managing field violet in vegetables crops. In carrots, linuron provides adequate control (Lipinski *et al.* 1979). Sulfosulfuron at 20 g ai ha^{-1} provided moderate control in potato (*Solanum tuberosum* L.) crops in Poland (Kuzior *et al.* 1999).

1.10.4 Control in other crops

Elliot and Jung (1980) observed adequate control of field violet in sugar beet with propham, chlorpropham, fenuron and metamitron. In green peas (*Pisum sativum* L.), PRE application of chlorthal dimethyl + methazole or cyanazine and POST application of dinoseb have resulted in a sufficient reduction of field violet (Handley and King 1976).

1.10.5 Control with non-selectives herbicides

Field violet is reportedly less susceptible to non-selective herbicides than most other dicotyledonous weeds. The efficacy of glufosinate ammonium is reportedly quite variable. Researchers in eastern Canada (CASCC 1998) observed suppression of 4–6-leaf plants when treated with a dose of 600 g ai ha^{-1}. However, 14 site-years of data from France (Pilorge and Mircovich 1999) and 6 site-years of data from northeastern Germany (Becker *et al.* 2001) indicate that, at doses of 600 and 1200 g ai ha^{-1} respectively, glufosinate ammonium is ineffective against field violet. Glyphosate did not control 4–6-leaf plants at 600 g ae ha^{-1} (Pilorge and Mircovich 1999), but did control field violet at 900 g ae ha^{-1} (CASCC 1998). In a greenhouse dose response assay conducted in Denmark, the effective dose of glyphosate required to reduce fresh weight of seedlings by 50% and 85% was found to be 298 and 1250 g ae ha^{-1}, respectively (Madsen and Streibig 1999). The corresponding values for a susceptible weed, *Brassica rapa*, were 207 and 360 g ae ha^{-1}, respectively.

1.10.6 Tolerance

Field violet is tolerant to most crop-selective herbicides. Over-wintering rosettes and quiescent plants exhibit the highest degree of herbicide tolerance (Doohan *et al.* 1991). Herbicide insensitivity has led to increased incidence of field violet in Europe and North America (Doohan and Monaco 1992; Hyvonen *et al.* 2003; Gummesson 1983; Makepeace 1978; USDA 2002). Hallgren *et al.* (1996) analyzed changes in the weed flora over a forty-year period in Sweden. They reported that the frequency of field violet increased in both spring and winter and this was inversely related to a gradual reduction in the efficacy of a common herbicide mixture (30 g L^{-1} dichlorprop + 130 g L^{-1} MCPA + 58 g L^{-1} ioxynil + 38 g L^{-1} bromoxynil). Doohan and Monaco (1992) reported tolerance to dicamba (0.4 kg ai ha^{-1}) and clopyralid (0.2 kg ai ha^{-1}). Other growth regulator herbicides, such as 2, 4-D and mecoprop, also have limited activity (Ontario Weed Committee 1988). Fluroxypyr treated plants show Group 4 symptoms shortly after application, but compensate with lateral shoot growth leading to plant recovery (Sanders and Pallett 1985b). Group 4 tolerance has been attributed to a lack of translocation and rapid conjugation to non-phytotoxic polar metabolites (Sanders and Pallett 1987b).

Photosynthesis inhibitors are generally ineffective, especially at low doses. Application of simazine (1.0 kg ai ha^{-1}), cyanazine (1.5 kg ai ha^{-1}), terbacil (0.25 kg ai ha^{-1}), bentazon and bentazon + bromoxynil + clopyralid (0.96 + 0.24 + 0.05 kg ai ha^{-1}) had little to no affect on field violet (Doohan *et al.* 1993; Froment and Turley 1998a). The nitrile herbicides ioxynil and bromoxynil gave very poor control of 4–6-leaf weeds when applied together (300 + 300 g ai ha^{-1}), or individually (bromoxynil K at 560 g ai ha^{-1}, ioxynil at 400 g ai ha^{-1}) (Pilorge and Mircovich 1999; Sanders and Pallett 1985a; Richardson and West 1985b). This tolerance of nitrile herbicides was reportedly not due to differential sensitivity of the binding site, as chloroplasts isolated from both field violet and scentless mayweed [*Tripleurospermum perforata* (Merat) M. Lainz], a sensitive species, showed similar responses to herbicide treatment (Sanders and Pallett 1985b). Further research indicated that tolerance may be due to increased production of granal thylakoids in treated leaves and the rapid metabolism of bromoxynil-K to halogenated metabolites (Sanders and Pallett 1986, 1987a). Doohan *et al.* (1993) reported that tolerance to terbacil, exhibited by mature plants (12-leaf stage), is the result of lower herbicide uptake, restricted translocation and increased metabolism to polar compounds. Most urea herbicides are not effective on field violet (Makepeace 1978). In herbicide experiments on winter flax, PRE application of linuron (0.75 kg ai ha^{-1}), linuron + terbacil (0.84 + 0.9 kg ai ha^{-1}) and linuron + trifluralin (0.37 + 0.67 kg ai ha^{-1}) did not have a significant affect on field violet (Froment and Turley 1998a).

Preemergence application of metazachlor, a chloroacetanilide family compound, did not control field violet (Bachthaler *et al.* 1986). Other Group 15 herbicides, such as napropamide and diphenamid, also conferred insufficient control (Chase and Putnam 1984). Surface applied, PRE trifluralin (Group 3) at 1.3 kg ai ha^{-1} did not significantly reduce field violet growth in experiments in the UK (Froment and Turley 1998a). Field violet was poorly controlled by florasulam (Group 2) when applied to winter wheat in Germany at a rate of 5 g ai ha^{-1} (Becker *et al.* 2000). Postemergence applications of amidosulfuron (60 g ai ha^{-1}), chlorsulfuron (20 g ai ha^{-1}) and imazethapyr (75 g ai ha^{-1}) also did not confer control in experiments conducted in eastern Canada and the UK (CASCC 1998; Richardson and West 1985b; West 1994).

1.10.7 Herbicide resistance

There have been no reports of herbicide resistant biotypes of field violet (Heap 2003). However, several studies have indicated a reduction in the efficacy of herbicides and herbicide combinations that previously gave full control (Bachthaler *et al.* 1986; Hallgren *et al.* 1996), possibly indicating a shift towards increased tolerance in field violet populations in some parts of Europe.

1.11 Cultural Management

1.11.1 Tillage

Reduced tillage may be an effective strategy to maintain population levels below economic thresholds in areas receiving moderate to high rainfall. Bachthaler *et al*. (1986) characterized field violet as having a requirement for soil disturbance to successfully germinate and complete its life cycle. It is well documented that minimal- or zero-tillage results in lower weed densities (Bujak 1996; Dzienia and Piskier 1998; Doohan *et al.* 1991; Froud-Williams *et al*. 1983, 1984; Nielson and Pinnerup 1982). Common to all of these studies was growing-season rainfall in excess of 35 cm. In Alberta, rainfall during the growing-season ranges from less than 20 cm in the dry parts of the prairies to more than 32.5 cm in the mountains, with the majority of agricultural land receiving less than 30 cm (Dzikowski and Heywood 1990). The effects of tillage regime under arid conditions have not been studied.

1.11.2 Crop density

Wilson *et al.* (1995) studied the influence of winter wheat density on weed biomass and weed seed production. Increasing crop density from 115 plants m^{-2} to 200 plants m^{-2} reduced weed biomass by an average of 24% and weed seed production by an average of 32%. Compared to a no-crop control, an established crop of 115 plants m^{-2} resulted in a 6-fold reduction in weed biomass and a 40-fold reduction in weed seed production. Similar results were reported by Ervio (1972), who noted a linear reduction in field violet growth as the sowing rate of cereals increased from 25 to 200 kg ha^{-1}.

1.11.3 Crop rotation

Field violet has been reported to increase in fields successively planted to grain crops (Bachthaler *et al.* 1986; Doohan and Monaco 1992). Weed density in spring-sown barley has been reported to be lower than in winter-sown wheat, possibly due to a competitive advantage of barley over wheat (Bourdot *et al.* 1998). In a 16-year study using a 3-crop rotation of sugar beets – winter wheat – winter barley, field violet density and seedbank deposition was found to be lower in winter wheat than in winter barley (Gerowitt and Bodendorfer 1998). The authors concluded that this was wholly or partially due to the competitive advantage of winter wheat over winter barley.

Seedbank and plant density in winter wheat remained stable over the study period, even when no herbicides were applied. Generally, field violet is less competitive in spring cereals than in winter cereals (Froud-Williams *et al.* 1983; Raatikainen *et al.* 1978). Doohan and Monaco (1992) reported that this may be due to the ability of winter annual field violet plants to continue growing after winter cereals have become dormant, thus giving the weed a competitive advantage the following spring.

1.11.4 Fertility

Above ground dry weight of individual field violet plants was reduced 30% when the rate of surface applied nitrogen decreased from 160 kg N ha^{-1} to 40 kg N ha^{-1} (Grundy *et al.* 1995). However, in competition with winter barley, not applying nitrogen resulted in the number of plants producing seed capsules increasing from 36 to 67% (Gerowitt and Bodendorfer 1998). Adding no fertilizer to a rotation of beets – winter wheat – winter barley resulted in the population of field violet increasing substantially due to the reduction of crop competition (Gerowitt and Bodendorfer 1998).

1.12 Biological Management

The polyphagous fungus, M. *acerina*, naturally infects field violet, causing blue-black lesions on leaves, petioles and flowers (Hermansen 1992; Rintelen and Klewitz 1976). Lawrie *et al.* (1999) evaluated the efficacy of M. *acerina* macroconidia, prepared in a rapeseed oil emulsion, sprayed on field violet foliage at the 4–7-leaf stage. When planted in pots with wheat, which is not affected by the pathogen, and sprayed with an inoculum concentration of 5×10^4 conidia mL^{-1}, field violet fresh weight was reduced to less than 0.1 and 25% of control values in glasshouse and outdoor experiments, respectively. Mortality at this inoculum level, 63 days after treatment, was 36% in outdoor studies and 92% in greenhouse studies. No commercial formulations of this mixture are currently available (Greaves and Lawrie 2001). A second pathogen, *Bremiella megasperma* (Berl.) G. W. Wilson, is known to cause downy mildew of field violet. To date, there are no reports that this pathogen has been formulated for use as a biocontrol (Farr *et al.* 1989).

1.13 Research objectives

This thesis presents the results of four site • years of research on the biology and management of field violet in direct-seeded wheat and canola crops in central Alberta. Field experiments were conducted in the summers of 2002 and 2003 at two sites (north of Lamont, AB and southeast of Ponoka, AB) that contained natural infestations of field violet. Additional experiments were conducted under controlled conditions in the greenhouse to supplement and verify the results of field experiments. This thesis is divided into three sections: (1) herbicide management alternatives for field violet in wheat crops of central Alberta, (2) herbicide management alternatives for field violet in canola crops of central Alberta, and (3) the biology of field violet.

1.13.1 Herbicide management alternatives for field violet in wheat

Field experiments evaluated control of field violet following POST application of nine herbicides (bentazon, florasulam + MCPA ester, fluroxypyr + 2,4-D ester, linuron, mecoprop + dicamba + MCPA, metribuzin, metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl) registered for use on bread wheat cultivars in Alberta. In 2003, the experiment was expanded to include pre-plant application of glyphosate and glyphosate + florasulam. All field experiments were planted to the hard red spring wheat cultivar AC Barrie. Relative activity of POST herbicides was determined without crop competition in a dose response experiment conducted in the greenhouse.

The objectives of this study were:

- To establish recommendations for control of field violet with herbicides registered for POST application on bread wheat in Alberta.
- To determine if a single PRE application of glyphosate or glyphosate + florasulam could provide agronomically acceptable control of field violet.
- To identify the herbicide treatments that maximize grain yield and dry matter accumulation of wheat when grown in competition with a natural weed community dominated by field violet.

The null hypotheses were:

- Field violet plant density, dry weight accumulation, height and reproductive potential would be identical between all POST herbicide treatments and the untreated control.
- Field violet in treatments receiving PRE glyphosate or glyphosate + florasulam would have identical plant density, dry weight accumulation, height and reproductive potential as field violet in treatments receiving POST herbicides.

- Wheat grain yield and dry matter accumulation in the herbicide treatments that provide agronomically acceptable control of field violet would be identical to that in the weed-free control.

1.13.2 Herbicide management alternatives for field violet in canola

Field experiments evaluated control of field violet following POST application of herbicides registered for use on conventional, glyphosate-tolerant, glufosinate-tolerant and imidazolinone-tolerant cultivars of canola. Cultivars were planted in adjacent experiments, one cultivar per experiment. Together, these cultivars allowed for the evaluation of the Group 2 products, imazamox + imazethapyr, ethametsulfuron-methyl and thifensulfuron, the Group 4 product, clopyralid, the Group 9 product, glyphosate and the Group 10 product, glufosinate ammonium. A separate experiment, planted to glyphosate-tolerant canola, was used to investigate the most effective time and rate of glyphosate application for control of field violet. This experiment evaluated glyphosate rates of 223 to 1335 g ae ha^{-1} and application timings of post-harvest (FALL), PRE, FALL + PRE and POST. Relative activity of POST herbicides was verified in a dose response experiment conducted in the greenhouse.

The objectives of this study were:

- To establish recommendations for control of field violet with registered POST herbicides in conventional, glyphosate-tolerant, glufosinate-tolerant and imidazolinone-tolerant cultivars of canola grown within Alberta.
- To determine if FALL, PRE or FALL + PRE applications of glyphosate could provide agronomically acceptable control of field violet.
- To identify the rate of glyphosate necessary to provide agronomically acceptable control of field violet in glyphosate-tolerant canola with a single POST application.
- To determine if canola seed yield and dry matter accumulation of treatments receiving a herbicide application differed from untreated controls when cultivars are grown in competition with a natural weed community dominated by field violet.

The null hypotheses were:

- For each cultivar, field violet plant density, dry weight accumulation, height and reproductive potential would be identical in all treatments receiving POST herbicide application and the untreated control.

- In glyphosate-tolerant canola, field violet receiving PRE , FALL and PRE + FALL applications of glyphosate would have identical plant density, dry weight accumulation, height and reproductive potential as field violet in treatments receiving POST herbicides.
- In glyphosate-tolerant canola, field violet plant density, dry weight accumulation, height and reproductive potential would be identical between the untreated control and all rates of glyphosate evaluated.
- Seed yield and dry matter accumulation of canola cultivars receiving herbicide treatments that provide agronomically acceptable control of field violet would be identical to that in the weed-free control.

1.13.3 Biology of field violet

Field violet population dynamics were examined in natural weed communities within one bread wheat cultivar (AC Barrie) and four canola cultivars (conventional — Q2, glufosinate-tolerant — Invigor 2663, glyphosate-tolerant — DKL 3455 and imidazolinone-tolerant — 45A77). Seed yield, seed weight, plant density and crop dry matter accumulation in weedy plots was compared to that in plots where weeds were removed by hand to quantify losses due to weed interference. This data was correlated to the field violet plant density (35, 55 and 85 days after planting), dry weight and relative dry weight [biomass of field violet / (biomass of crop + field violet)] in each plot to evaluate the competitiveness of this weed. The phenology and periodicity of field violet emergence, flowering and seed set was investigated in plots seeded to wheat. These plots were also used to observe the reproductive potential of field violet when competing with wheat. A greenhouse experiment investigated the morphology, growth staging and reproductive potential of field violet under ambient conditions. This experiment also analyzed the genetic component of intraspecific variation in field violet by comparing the growth and development of two distinct populations under identical conditions. The comparisons were made between a naturalized population found in fields of Alberta and a native population endemic to the United Kingdom.

The objectives of this study were:

- To quantify the effects of field violet density, dry weight and relative dry weight [dry weight of field violet / (dry weight of crop + field violet)] on seed yield, seed weight, dry weight accumulation and plant density of spring wheat, conventional canola, glufosinate-tolerant canola, glyphosate-tolerant canola and imidazolinone-tolerant canola.

- To determine if crop / cultivar selection has a significant effect on field violet density, dry weight accumulation, height or reproductive potential in plots containing a natural weed flora.
- To characterize the periodicity and phenology of emergence, flowering and seed set in field violet and determine the length of time required to reach reproductive maturity under average and optimal field conditions.
- To investigate the morphology of field violet under controlled conditions in a greenhouse and determine the temporal length of each growth stage and the reproductive potential of the weed under greenhouse conditions.
- To differentiate any variation in morphology, reproductive potential, dry weight accumulation or seed weight between the population of field violet found in Alberta and a population from Europe, when grown under identical conditions in a controlled environment.

The null hypotheses were:

- In all crop cultivars evaluated, field violet density, dry weight and relative dry weight would not differ based on crop seed yield, seed weight, dry weight accumulation or plant density.
- Field violet density, dry weight accumulation, height and reproductive potential would be identical in all crop cultivars and between crop species.
- Field violet emergence would not differ during any period during the growing season.
- No correlation would exist between field violet emergence and any specific weather event.
- The length of time required to reach reproductive maturity under field conditions would not be affected by weather patterns.
- Field violet growth under greenhouse conditions will occur at the same rate as when the plants are growing under field conditions.
- Plants reared in the greenhouse will have identical reproductive potential as plants growing under field conditions.
- Seedlots of field violet from Alberta and Europe will produce morphologically and reproductively identical plants when grown under identical conditions.

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Chapter 2

Herbicidal management of field violet (*Viola arvensis* Murr.) in wheat (*Triticum aestivum* L.)

2.1 Introduction

Field violet (*Viola arvensis* Murr.) is a weed of arable land that is a problem globally where cereal crops are grown (Doohan and Monaco 1992; Wiersema and Leon 1999). It has an annual or winter annual growth habit, although in Canada it can also be a short-lived perennial (Alex and Switzer 1976). Field violet is cold-, shade- and drought-tolerant, capable of colonizing acid and alkaline soils and has been reported to have a preference for tilled, arable land (Bachthaler *et al.* 1986; Doohan and Monaco 1992). Flowering is indeterminate and individual plants can produce as many as 46,000 seeds under optimal growing conditions (Doohan and Monaco 1992). Seeds exhibit variable dormancy, allowing plants to emerge periodically throughout the growing season (Baskin and Baskin 1995).

Field violet is one of the most common weeds of cereal crops in Europe, where it is endemic (Holm *et al.* 1979; Schroeder *et al.* 1993). It has been found in 70% of wheat and barley fields surveyed in Canterbury, New Zealand (Bourdot *et al.* 1998). In weed surveys in New Brunswick (Doohan 1985) and the L'Assomption / Richelieu regions of Québec (Doyon *et al.* 1986a, 1986b), field violet was observed in 10 to 20% of cereal fields. It has been noted in wheat and barley crops of Saskatchewan (Thomas *et al.* 1996) and was recently identified in Alberta reduced-tillage cereal fields.

There have been no studies evaluating spring wheat yield loss due to interference from field violet in western Canada. In Sweden, seed yield of spring-sown wheat and barley crops was not affected by interference from field violet at a density of 33 plants m^{-2}, seven weeks after planting (Boström *et al.* 2003). Field violet is reportedly more competitive in winter cereals (Froud-Williams *et al.* 1983; Raatikainen *et al.* 1978), although production losses in these crops are variable. In research at Bristol, UK, Wilson and Wright (1990) compared yields of winter wheat when competing with each of 12 annual weeds. They found that field violet was the least competitive, conferring the smallest reduction in grain yield. In other experiments conducted at the same research station, field violet reduced yield of winter cereals by an average of 2% at a density of 109 plants m^{-2} (Wilson 1989). In an experiment investigating the effect of crop density on yield loss due to competition with weeds, field violet (636 plants m^{-2}) caused winter wheat yield losses of 30, 15 and 4% at crop densities (8 weeks after planting) of 39, 116 and 207 winter wheat plants m^{-2}, respectively (Wilson *et al.* 1995).

Seeds of field violet may be harvested with grain crops. Bourdot *et al.* (1998) noted that it was the fifth most frequent weed above 15 cm (harvest height) at crop maturity in winter wheat. Harvested samples of winter barley contained as many as five field violet seeds for every field violet plant present at harvest (Gerowitt and Bodendorfer 1998). Bachthaler *et al.* (1986) reported that harvested weed tissue could increase the moisture content of harvested grain.

Most crop-selective herbicides in wheat do not control field violet. Overwintering rosettes and quiescent plants exhibit the highest degree of herbicide tolerance (Doohan *et al.* 1991). The weed was not controlled by dicamba at 0.4 kg ai ha^{-1} (Doohan and Monaco 1992) and was classified as tolerant to 2, 4-D and mecoprop (Ontario Weed Committee 1988). Fluroxypyr was found to be ineffective because the active form of the herbicide is not readily translocated and is rapidly conjugated to non-phytotoxic polar metabolites (Sanders and Pallett 1987b). Application of bentazon and bentazon + bromoxynil + clopyralid (0.96 + 0.24 + 0.05 kg ai ha^{-1}) had no affect on field violet (Froment and Turley, 1998). Additionally, neither bromoxynil K (0.5 kg ai ha^{-1}) or ioxynil (0.4 kg ai ha^{-1}) provided control of field violet when applied after the 4-leaf stage (Sanders and Pallett 1985a; Richardson and West 1985). Tolerance to these two herbicides, and others from the nitrile family, has been attributed to increased production of granal thylakoids in treated leaves and rapid metabolism of active compounds to halogenated metabolites (Sanders and Pallett, 1985b, 1986, 1987a). Linuron, applied preemergence (PRE) at a rate of 0.75 kg ai ha^{-1} did not affect field violet growth (Froment and Turley, 1998) and Makepeace (1978) generalized that most urea herbicides are not effective. The weed was poorly controlled by florasulam applied at 5 g ai ha^{-1} (Becker *et al.* 2001). Postemergence (POST) applications of amidosulfuron (60 g ai ha^{-1}), chlorsulfuron (20 g ai ha^{-1}) and imazethapyr (75 g ai ha^{-1}) also did not confer control [Canadian Agricultural Services Coordinating Committee (CASCC) 1998; Richardson and West 1985].

Effective chemical management of field violet in cereal crops of Europe has relied on the sulfonylureas and herbicide mixtures containing active ingredients with more than one mode of action (Doohan and Monaco 1992; Roberts and Bond 1983, 1984). In spring barley it has been controlled with metsulfuron methyl (6 g ai ha^{-1}), tribenuron-methyl (5.3 g ai ha^{-1}), triasulfuron (7.5 g ai ha^{-1}) and terbutryn + triasulfuron (300 + 20 g ai ha^{-1}) (Davies and Wilson 1997; Dovydaitis, 1997; Salonen, 1993). Herbicide evaluations in two spring-planted *Poaceae* family crops (*Phalaris aquatica* L. and *Dactylis glomerata* L.) in Argentina found that adequate control of field violet, 4 weeks after treatment (WAT), was obtained with metsulfuron + dicamba (3 + 38 g ai ha^{-1}) and triasulfuron + terbutryn + dicamba (4 + 120 + 48 g ai ha^{-1}) (Bedmar *et al.* 1995, 1996). There are no reports of effective chemical controls for field violet control in spring cereal crops in western Canada.

Timing of herbicide application may alter the response of field violet, as herbicide rates required for control in winter crops, where the weed can be targeted at the more susceptible stages prior to the onset of winter dormancy, are generally less than comparable rates in spring crops. In winter wheat, POST metsulfuron methyl (4 g ai ha^{-1}) and PRE amidosulfuron (15 g ai ha^{-1}) conferred control (Christie and Cornwell 1984; West 1994). The mixture of clopyralid + fluroxypyr + ioxynil (56 + 180 + 180 g ai ha^{-1}) suppressed weed growth, reducing weed biomass, the number of capsules per plant and the number of seeds per capsule by 50, 50 and 10%, respectively (Grundy *et al.* 1995). Mixtures providing agronomically acceptable control in winter wheat include isoproturon + ioxynil + mecoprop, isoproturon + bifenox + bromoxynil, metsulfuron methyl + thifensulfuron methyl, isoproturon + bifenox + fluroxypyr, linuron + bifenox and mecoprop + tribunal (Gerowitt and Bodendorfer 1998; Jenneus 1983; Lake 1974).

The objective of this study was to evaluate field violet control obtained with herbicides registered for POST application on hard red spring wheat in Alberta, employing both field experiments and dose response assays in a controlled environment. A secondary objective was to determine if a PRE application of a non-selective herbicide without residual activity (glyphosate), or a non-selective herbicide with residual activity (glyphosate + florasulam), could maintain season-long control of field violet in spring wheat.

2.2 Materials and Methods

2.2.1 Field Experiments

Experiments were conducted in 2002 and 2003 in commercial fields northeast of both Lamont (53° 52' N 112° 39'W) and Lacombe (52° 32' N 113° 18'W), AB (Figure 2.1). Fields contained natural infestations of field violet and were managed under a reduced-tillage regime, where residue from previous crops was left on the soil surface, seeding was performed with a low-disturbance air-drill and tillage was limited to occasional harrowing. Experimental sites were at least 20 m from field boundaries on reasonably level ground with a relatively uniform weed density (Appendix B, Figure B.2.1). In the second year of the study, experiments were moved to adjacent, non-overlapping locations within the same fields. Land used for experiments at the Lamont site in 2002 and 2003 was in barley (*Hordeum vulgare* L.) the preceding year. At the Lacombe site, the land used for experiments in 2002 and 2003 was in common oat (*Avena sativa* L.) and barley, respectively, in the preceding year. The soil at Lamont was a black solodized solonetz, Camrose series (Alberta Soil Information Centre 2001), with a loam to sandy loam soil texture, a pH of 5.6–6, 2.3–2.7% organic matter and 49–58, 30–38 and 12–14% sand, silt and clay, respectively. The soil at Lacombe was an orthic black chernozem, Peace Hills series (Alberta Soil Information Centre 2001), with a sandy loam texture, a pH of 5.2–5.4, 2.0–2.7% organic matter and 64–66, 24–26 and 10% sand, silt and clay, respectively. Edaphic properties and soil fertility were determined from analysis[1] of bulk samples of four soil cores, 6 cm diameter and 19 cm deep, taken each spring.

Hard red spring wheat (cv. AC Barrie) was sown on May 14–24 (Table 2.1). Seed was planted to a depth of 3–4 cm into rows 20.3 cm at a rate of 285–303 seeds m^{-2}, using a minimal-disturbance air-seeder equipped with double-shoot, single side band openers and individual row packers. At seeding, nitrogen (100 kg N ha^{-1} as NH_4) was banded beneath seed rows to a depth of 8 cm; phosphorus (P_2O_5), potassium and sulfur (K_2SO_4) were deposited with the seed at rates of 25 kg P ha^{-1}, 60 kg K ha^{-1} and 20 kg S ha^{-1}, respectively. Individual plots were 8.5 m long, 2 m wide with six wheat rows. In-crop herbicides were applied with a CO_2-pressurized self-propelled sprayer shortly after wheat plants had initiated tillering (3- to 5-leaf stage). The sprayer was equipped with 11015 TeeJet flat fan nozzles calibrated to deliver a spray volume of 100 L ha^{-1} at 207 kPa. Preemergence applications were applied with a backpack sprayer, equipped with 11015 TeeJet[2] flat fan nozzles, calibrated to deliver 100 L ha^{-1} at 152 kPa using CO^2 as a propellant. Application dates varied between sites and years (Table 2.1). POST herbicides targeted field violet plants at the cotyledon to 10-leaf stage, except in Lamont in 2002, where weeds ranged from cotyledon to large, flowering plants. PRE herbicides targeted predominantly smaller (cotyledon to 4-leaf) spring-emerged plants, with larger perennated plants comprising an average of 18 to 21% of the total plant density (data not shown). Grass weeds were controlled at the 1- to 3-leaf stage in 2003 and the 1- to 6-leaf stage in 2002, with clodinafop-propargyl (56 g ai ha^{-1}), applied separately. Graminicide application in 2002 was delayed to allow a second flush of grass weeds to be targeted with a single application. In Lamont in 2003, Canada thistle [*Cirsium arvense* (L.) Scop.] and volunteer barley infestations occurred. Clopyralid (202 g ai ha^{-1}) was applied to the wheat crop at the 2- to 4-leaf stage to remove Canada thistle, but volunteer barley could not be controlled and was adjusted for in harvested grain samples.

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[1] Analysis performed by Norwest Labs, 7217 Roper Road, Edmonton, AB, Canada, T6B 3J4.

[2] Spraying Systems Co.,425 J Meyer Road, Uniontown, WA, 99179.

Experimental design was a randomized complete block with four blocks. Each block contained all herbicides and application timings being evaluated (Table 2.2), as well as an untreated control and a weed-free control established by applying glyphosate at 1334 g ai ha^{-1} prior to crop seeding and maintained by hand roguing weeds as they emerged. Herbicide rates selected for experiments were chosen based on label recommendations outlined in the Alberta Crop Protection Guide (Ali, 2003). For bentazon, linuron, metribuzin and MCPA + mecoprop + dicamba, where a range of POST application rates was permissible, the selected rate represented the highest recommended rate. The glyphosate rate selected for PRE application was chosen to allow for direct comparison with the commercial PRE glyphosate + florasulam[3] treatment.

A visual estimate of field violet control, hereafter referred to as control, was evaluated 1, 2, 4 and 8 weeks after POST herbicide application (WAT) and rated on a 100 point scale (0 = no control, 100 = complete plant mortality). Acceptable control of field violet was judged as a rating of ≥70% control 8 WAT, and required that the most plants were killed and that survivors had no or very little reproductive capability. Suppression of weed growth was denoted by a rating of 50–69% control. Weeds were non-destructively counted in two 0.25 m^2, randomly selected, quadrats within rows 2–5 of each plot immediately following herbicide application, and 4 and 8 WAT. Counted weeds were categorized as either small (cotyledon to 4-leaf stage) or large (beyond the 4-leaf stage). Due to large fluctuations in the density of small weeds, only large weed density is presented, unless otherwise mentioned. Wheat plants were counted after anthesis in two, randomly selected, 0.25 m^2 quadrats from within rows 2–5 of each plot. Crop and weed biomass samples were collected 5 WAT by harvesting all plants at ground level from three 0.25 m^2, randomly selected, quadrats within rows 2–5 of each plot. Biomass samples were subsequently placed in a dryer at 60 °C for 72 hours and weighed. Measurements of field violet height (ground to stem apex) and the number of reproductive units (viable flowers, dehisced and non-dehisced seed capsules) per plant were taken 8 WAT in 2003 and, due to environmental conditions, 4 WAT in 2002.

At crop maturity, all plots were desiccated with a foliar application of diquat (385 g ai ha^{-1}). Seven to ten days after desiccation a 7.1 m^2 portion of each plot was harvested with a straight-cut plot combine, dried thereafter at 60 °C for 72 hours, cleaned and the seed weight per plot and

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[3] PrePass™, Dow AgroSciences Canada Inc., 201, 1144-29 Avenue NE, Calgary, AB, Canada, T2E 7P1.

1000-kernel weight were recorded. For grain samples from Lamont in 2003, contaminant barley from within 50 g subsamples was separated and weighed to calculate sample dockage (barley weight ÷ total subsample weight). Dockage was not significantly different between treatments ($P = 0.79$) and averaged 10% (SEM = 1.5%, $n = 51$). Dockage adjusted sample weights [sample weight × (1 - dockage)] were used for all analyses.

All results were analyzed within mixed models, with locations and blocks considered random, and herbicide effects considered fixed (SAS Institute Inc. 1999). Year effects were initially included and considered fixed, but years were ultimately analyzed separately due to heterogeneous error variances and significant year × herbicide interaction, both of which were presumably the result of extreme differences in precipitation between years (Table 2.1). The denominator degrees of freedom used to calculate the significance of fixed effects were adjusted using the method outlined by Kenward and Roger (1997). Weed control and plant density data collected 2, 4 and 8 WAT were combined and analyzed as repeated measures over time, allowing for error mean squares to be adjusted for covariance between temporal observations. In this model, location and block effects were again considered random and herbicide, week (after herbicide application) and herbicide × week effects considered fixed. Quantitative data (crop and weed biomass, seed yield, weed plant density, weed height and weed reproductive potential) were square root transformed $[(x+1)^{0.5}]$ prior to analyses to normalize the distribution of residual error and reduce heteroscedasticity (Steel and Torrie 1980). Field violet plant density, biomass, height and reproductive potential in herbicide treated plots were compared to the untreated controls via orthogonal contrasts of transformed data (Steel and Torrie 1980). Additional contrasts of transformed data were used to compare wheat seed yield, kernel weight, plant density, and biomass in herbicide treated plots to both untreated and weed-free controls. To simplify interpretation of results, least square means of untransformed data are presented along with P-values and mean separations from transformed data (Tabachnick and Fidell 2001). Back-transformations of data were not conducted. Differences between herbicide treatments are considered significant when $P < 0.05$.

2.2.2 Greenhouse dose response assay

A dose response assay was conducted in the University of Alberta greenhouse in 2003. Seeds harvested from field violet plants growing in the Andrew Plain ecodistrict of Alberta were increased in the greenhouse in the winter and spring of 2002 and seeded into flats containing six, 13 × 18 cm trays of a soilless vermiculite-peat mixture (Metro-Mix 290[4]). Flats were watered and placed in a greenhouse (16 hour photoperiod, 21 °C average temperature) until plants reached the one- to two-leaf, at which they were thinned to 12 per tray. Each flat was an experimental unit. Flats of plants were sprayed at the 3- to 4-leaf stage (3 weeks after planting) with rates selected to verify data obtained from field experiments and to identify the rates required to cause 50 and 85% reductions in weed dry biomass (Table 2.3). Herbicides were applied with an indoor track sprayer outfitted with a low-drift air bubblejet nozzle[5], calibrated to apply 200 L ha^{-1} at 200 kPa. Following herbicide application, trays were returned to the greenhouse and irrigated from above as required. All trays were fertilized one week after herbicide application with 250 mL of a 1 g L^{-1} solution of 20:20:20 complete fertilizer. The entire experiment was repeated four times. There were therefore 45 herbicide treatments, with four blocks in time, and the experiment was considered a randomized complete block.

Plants from each tray were counted and scored for control every seven days after herbicide application for 28 days. A nine-point rating scale (1–9) was used to rank herbicide injury, with 1 representing no signs of herbicide injury and 9 representing 100% plant mortality. Immediately following the final scoring (28 days after application), plants were removed from trays at ground level and fresh weights recorded. Samples were dried for 24 hours in an oven at 60 °C and weighed to determine biomass.

Treatment effects were analyzed within mixed models with blocks in time considered as random and rate effects considered fixed. The denominator degrees of freedom used to calculate the significance of fixed effects were adjusted using the method outlined by Kenward and Roger (1997). Least square means of the biomass of field violet at each herbicide by dose combination are presented. Differences in least squares are discussed only when $P < 0.05$. Single degree of freedom contrasts were used to test for linear, quadratic or cubic responses of field violet biomass to herbicide rate. This response was found to be nonlinear for all treatments, and hence biomass data were fit to a four parameter log-logistic curve (Seefeldt *et al.* 1995) using the NLIN procedure of SAS (SAS Institute Inc. 1999). The resultant models were used to estimate ED_{50} and ED_{85} values and to calculate estimates of corresponding asymptotic standard errors.

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[4] The Scott's Company, 14111 Scottslawn Road, Marysville, OH, USA, 43041.

[5] ABJ Agri Products, 49 Cherry Crescent, Brandon, MB, Canada, R7B 0Y3.

2.3 Results and Discussion

2.3.1 Weather conditions

Both experimental locations experienced severe drought in 2002 (Table 2.1), receiving 4.2–6 mm rain in the four weeks preceding, and 17.5–31 mm rain in the four weeks following herbicide application. At Lacombe, early season drought was partially mediated by significant moisture from snow melt. Lamont had limited snowfall, which further intensified drought conditions caused by low rainfall. Rainfall was greater in 2003, although it remained well below the 30-year ecodistrict average (Agriculture and Agri-Food Canada 1999) at Lacombe. This had limited effects on herbicide activity or crop production because the majority (57%) of total precipitation fell in May and June, during the critical period of crop establishment. Average temperatures were very close to ecodistrict normals in both 2002 and 2003.

2.3.2 Efficacy of in-crop herbicides

Most herbicides were less effective in 2002 than in 2003 (Table 2.4). In 2002, only fluroxypyr + 2,4-D LV ester 600 provided control of field violet, reducing weed biomass 5 WAT and plant density 8 WAT by 59 and 91%, respectively, from untreated controls (Table 2.4–2.5). Suppression (mean control ≥ 50%) was observed in plots receiving POST application of MCPA + mecoprop + dicamba, metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl (Table 2.4). Field violet plant density in these plots 8 WAT was 25–67% less than untreated controls, although this was only significant for MCPA + mecoprop + dicamba and metsulfuron methyl (Table 2.5). Biomass in these plots was also less than in the untreated controls by 27 (metsulfuron methyl) to 78% (thifensulfuron methyl + tribenuron methyl). POST application of metribuzin reduced field violet density and biomass, providing suppression ($\bar{x}$ control = 63%) at Lacombe, but had only minor observable effects at Lamont ($\bar{x}$ control = 5%) (data not shown).

In 2003, the Group 2 (Mallory-Smith and Retzinger 2003) herbicides metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl provided good control of field violet. Plant density following application was 82–92% less than initial densities and 81–89% less than untreated control densities, 8 WAT (Table 2.5). Biomass 5 WAT was reduced by 45–73% (Table 2.4). Plants treated with these herbicides ceased growing shortly after application and developed symptoms typical of acetolactate-synthase inhibition (wilting, chlorosis, necrosis, leaf abscission), which ultimately led to plant death. Only large (6- to 10-leaf) perennated plants survived application, however these plants were effectively sterile, producing less than 1 reproductive unit per plant. Florasulam + MCPA ester (Group 2 + 4) had no affect on field violet growth. Becker *et al*. (2001) also found that field violet was poorly controlled by florasulam in winter wheat crops of Germany.

Activity of fluroxypyr + 2, 4-D LV ester 600 in 2003 was consistent with activity in the 2002, conferring 69, 83 and 86% reductions in weed biomass 5 WAT, plant density 8 WAT and reproductive potential, respectively, relative to the untreated control (Table 2.4–2.5). Application of MCPA + mecoprop + dicamba, which has the same mode of action as fluroxypyr + 2, 4-D LV ester 600, suppressed field violet, reducing plant density, biomass and reproductive potential by 55–60%. Suppression was also observed in plots treated with metribuzin, which caused chlorosis and defoliation of treated plants. Small (< 5 leaf) field violet plants did not recover from this injury, resulting in plant density and biomass reductions of 54 and 86%, respectively, relative to untreated controls (Table 2.4–2.5). Larger plants partially compensated for injury by vigorous growth from axial nodes, which reduced the effects of this herbicide on plant reproductive potential ($\bar{x}$ = 6.5 reproductive units plant^{-1} 8 WAT, range: 0–25). This finding is consistent with those from Europe, where the weed is reported as only moderately susceptible to POST metribuzin at rates of 525–1050 g ai ha^{-1} (Makhteshim Agan UK Ltd. 2002). Application of linuron or bentazon in the present study caused only minor symptoms of injury to field violet, from which plants rapidly recovered, allowing for full expression of reproductive potential and no reduction in plant density or biomass.

Differences in herbicide activity between years may have been due to growing conditions at the time of herbicide application. In 2002, severe water-stress early in the growing season may have forced drought-tolerant field violet plants into a quiescent state where they were less affected by herbicide activity and were able to recover rapidly following subsequent precipitation events. In 2003, soil moisture was adequate to excellent at both locations at the time of herbicide application. Consequently, field violet plants were actively growing and herbicide uptake and activity were unhindered. Other researchers have reported reduced efficacy of herbicides when soil moisture is limiting. Activity of metribuzin on downy brome (*Bromus tectorum* L.) was found to be two- to threefold less when soil moisture was poor (-1.5 MPa) than when soil moisture was adequate (-0.03 MPa) (Blackshaw *et al*. 1994). Bailey and Wilson (2003) reported less control of Italian ryegrass [*Lolium perenne* ssp. *multiflorum* (Lam.) Husnot] with metsulfuron + chlorsulfuron (4.3 + 21.7 g ai ha^{-1}) and sulfosulfuron (35 g ai ha^{-1}) in a year with no precipitation two weeks prior to herbicide application, than in a year with 30.5 mm of precipitation during the same period. Similar findings have been reported with other foliage-applied Group 2 herbicides (Bruce *et al.* 1996; Lundkvist 1997; Xie *et al.* 1997).

Activity of all herbicides was greater in the greenhouse, when herbicides were applied to 3- to 4-leaf field violet plants (Appendix B, Figure B.2.2). Estimated ED_{85} values for metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl, fluroxypyr + 2, 4-D LV ester 600 and metribuzin were less than the recommended rate used in field experiments (Figure 2.2 A–E). With the exception of metribuzin, these products also provided excellent control in field experiments. Greater activity of metribuzin in the greenhouse may have been due to greater spray volume employed and smaller target plants, both of which have been shown to improve efficacy of this herbicide on weeds (Das and Yaduraju 2002; Ketel *et al.* 1996). Estimated ED_{85} values for florasulam + MCPA ester and MCPA + mecoprop + dicamba were slightly greater than the rates used in field experiments (107–121%), whereas estimated values for linuron and bentazon were much greater (187–364%) than rates evaluated in the field (Figure 2.2 F–I). These results were similar to the activity observed in field experiments, except for florasulam + MCPA ester, which had virtually no affect on field violet in field experiments, suggesting that this herbicide is only active on smaller (< 5-leaf) field violet plants. Differential activity of florasulam + MCPA ester due to weed staging has not been reported previously, but other studies have found that ALS-inhibiting herbicides are less active on larger weeds (Rosales *et al.* 1999; Swanton and Chandler 1990).

Application of postemergence herbicides generally had no affect on crop production (Table 2.6). The lack of a yield response to herbicide application was likely an indication of the weakly competitive nature of field violet (Semb 1996a, 1996b, 1996c) and the variable effects of biotic (*Poaceae*-family weeds and barley) and abiotic (drought) stresses on crop production.

2.3.3 Efficacy of pre-emergence herbicides

Preemergence application of glyphosate provided acceptable season long control of field violet at both locations in 2003. Eight weeks after in-crop herbicide application, weed plant density was 56% lower in plots receiving PRE glyphosate than in untreated plots (Table 2.5). Weeds within these plots accumulated little above-ground biomass (< 0.5 g m^{-2}) and had low reproductive potential (< 3 reproductive units $plant^{-1}$). The addition of florasulam, a Group 2 herbicide with residual activity, to glyphosate did not significantly improve control over that obtained from glyphosate alone.

Adequate weed control following a single PRE application of glyphosate is uncommon. Blackshaw *et al.* (1998, 2000) reported that acceptable control of foxtail barley (*Hordeum jubatum* L.) could only be obtained if a PRE glyphosate application was followed up by a second in-crop application of a selective herbicide. Similarly, late emerging cohorts of common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and yellow foxtail [*Setaria pumila* ssp. *pallidifusca* (Schumacher) B. K. Simon] significantly reduced soybean yield in field experiments conducted in southern Ontario (Swanton *et al.* 2000). The effectiveness of PRE glyphosate on field violet within crop was likely due to the susceptibility of young plants to glyphosate and the inability of subsequently emerging plants to compete with crop and other weed species. A reduction in field violet density and growth rate due to increased populations of competitors has been reported in other studies (Bachthaler *et al.* 1986; Gerowitt and Bodendorfer 1998; Mukula *et al.* 1969).

Crop biomass and seed yield were not different ($P > 0.05$) between PRE and POST treatments or between PRE and control (weed-free, untreated) treatments (Table 2.6). Treatments applied PRE tended to have a greater population of dicotyledonous weeds other than field violet (data not shown), which negated the yield advantage that may have been realized by early weed removal.

2.4 Summary

Control of field violet with POST herbicides was more difficult under drought conditions. Only fluroxypyr + 2, 4-D LV ester 600 provided control of field violet when precipitation was less than 15 cm during the growing season. This finding contradicts previous reports classifying field violet as moderately tolerant of fluroxypyr (Sanders and Pallett 1987b) and suggesting that the efficacy of this herbicide is lower under drought conditions (Bouma *et al.* 1996; Hannan-Jones 1998). However, in the present study it may be that application of this herbicide compounded injury due to drought-stress by stimulating auxin-regulated growth during a period when most plants had become quiescent. This may have depleted water and carbohydrate reserves necessary for survival, ultimately leading to plant mortality.

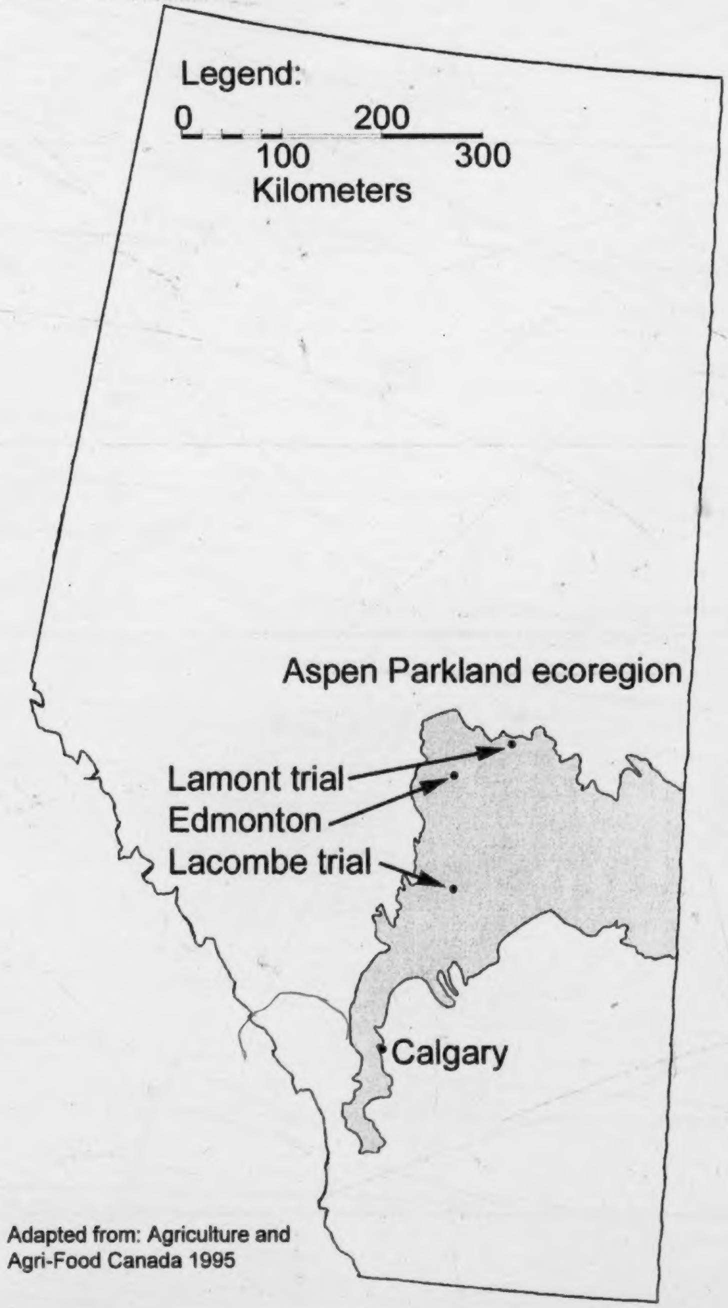
When rainfall is not limiting, field violet can be effectively controlled by Group 2 herbicides, although results suggest that not all members of this group are equally efficacious. Metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl provided excellent control of field violet that was maintained throughout the growing season. Similar findings have been reported with these herbicides on winter and spring cereal crops in Europe (Christie and Cornwell 1984; Davies and Wilson 1997).

Glyphosate, applied PRE, provided agronomically acceptable control of field violet throughout the growing season. Success of this application will likely require that crop establishment occurs rapidly following application due to the ability of this weed to emerge in intermittent flushes throughout the growing season (Doohan *et al.* 1991; Ervio 1972). Field violet plants emerging subsequent to establishment of a competitive crop stand would likely have few effects on crop production.

Wheat seed yield and biomass were not consistently affected by POST or PRE herbicide application to control field violet. Preemergence herbicide application has been shown to improve crop yield by reducing interference from weeds at the critical period of establishment (Johnson *et al.* 2002; Martin *et al.* 2001). Weeds emerging after PRE herbicide application and prior to canopy closure may have limited the effectiveness of this strategy in our experiments. Removing this late flush of weeds with a POST herbicide may be required to maximize yield. Yield increases when a PRE application of glyphosate is followed by a selective POST herbicide have been reported for other crops (Broome *et al.* 2000; Heatherly *et al.* 1994).

Management of field violet is possible with postemergence herbicides registered for use on spring wheat in Alberta. Where crop rotation prevents the application of an effective POST herbicide, PRE glyphosate or glyphosate + florasulam can be applied in some crops. The weed does not appear to cause significant crop production losses and thus herbicide selection should be based on knowledge of all species present within the weed flora. As growth of field violet is limited by interspecific competition, weed management strategies should also include cultural techniques designed to improve relative crop competitiveness, such as selecting wheat cultivars with vigorous growth, reducing row spacing and increasing seeding rate (Koscelny *et al.* 1998; Roberts *et al.* 2001).

2.5 Tables and figures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Kilometers
Aspen Parkland ecoregion
Lamont trial
Edmonton
Lacombe trial
Calgary
Adapted from: Agriculture and Agri-Food Canada 1995

Figure 2.1 Location of field trials used to evaluate the efficacy of pre- and postemergence herbicides on field violet within spring wheat in 2002 and 2003.

Table 2.1 Planting, herbicide application and harvest dates, accumulated precipitation and growing degree days (5 °C) during the growing season (May to September) for Lacombe and Lamont trial sites in 2002 and 2003.

		Dates of management practices				Accumulated precipitation and growing degree days from May to September												Accumulated Prec. and GDD as a % of the 30-year average for respective ecodistricts[a]	
		Crop	lerbicide applicatic		Grain	Precipitation						Growing Degree Days (base = 5 °C)							
Site		seeding	PRE	POST	harvest	May	Jun	Jul	Aug	Sep	Total	May	Jun	Jul	Aug	Sep	Total	Prec.	GDD
						mm						degree • days						%	
Lacombe	2002	May 24	-	Jun 24	Sep 18	2	7	38	49	21	116	177	347	387	255	125	1291	36%	100%
	2003	May 15	May 15	Jun 16	Sep 04	66	41	20	29	33	188	165	269	393	392	146	1365	59%	106%
Lamont	2002	May 17	-	Jun 21	Sep 27	5	17	60	54	11	147	203	374	425	307	154	1462	49%	111%
	2003	May 14	May 14	Jun 12	Sep 05	73	88	60	39	61	321	188	270	363	355	146	1323	108%	100%

Abbreviations: POST, post-crop emergence; PRE, pre-planting; GDD, growing degree days; Prec., Precipitation.

[a] Agriculture and Agri-Food Canada 1999.

Table 2.2 Herbicides, rates and application timings evaluated for control of field violet in spring wheat in field experiments conducted at Lacombe and Lamont in 2002 and 2003.

Herbicides evaluated	Rate	Adjuvant (Rate)	Application Timing
	— g ai ha^{-1} —		
Bentazon	1079	Assist Oil Concentrate (1% v / v)	POST
Glyphosate[a]	445	-	PRE
Glyphosate + florasulam[a]	450 + 5	-	PRE
Florasulam + MCPA Ester	5 + 414	-	POST
Fluroxypyr + 2,4–D LV ester 600	107 + 557	-	POST
Linuron	261	-	POST
MCPA + mecoprop + dicamba	408 + 93 + 93	-	POST
Metribuzin	278		POST
Metsulfuron methyl	4	Agral 90 (0.2% v / v)	POST
Sulfosulfuron	20	Merge (0.5 L ha^{-1})	POST
Thifensulfuron methyl + tribenuron methyl	10 + 5	Agral 90 (0.2% v / v)	POST

Abbreviations: POST, post-crop emergence; PRE, pre-planting; v / v, volume per volume

[a] Pre-plant applications were included in 2003 only.

Table 2.3 Herbicides and rates evaluated for control of field violet in the greenhouse in 2003.

Group 2 Heribicides[†]			Group 4, 5, 6 and 7 Heribicides[†]		
	Greenhouse application rate			Greenhouse application rate	
Herbicide	Rate	Relative to recommended field rate	Herbicide	Rate	Relative to recommended field rate
	– g ai ha^{-1} –	— % —		– g ai ha^{-1} –	— % —
Florasulam + MCPA ester 500[α] (Group 2 + 4)	4 + 335	80	Fluroxypyr + 2,4–D LV ester 600 (Group 4)	25 + 131	25
	5 + 419	100		55 + 287	50
	8 + 670	160		80 + 418	75
	10 + 838	200		110 + 574	105
	15 + 1256	300		135 + 705	125
Metsulfuron methyl	1	20	MCPA + mecoprop + dicamba[γ] (Group 4)	150	150
	2	45		445	100
	3	65		590	150
	4	90		740	200
	5	110		1035	300
Sulfosulfuron	10	50	Metribuzin (Group 5)	140	50
	15	75		210	75
	20	100		280	100
	25	125		420	150
	30	150		560	200
Thifensulfuron methyl + tribenuron methyl[β] (Group 2)	8	55	Bentazon (Group 6)	810	75
	11	75		1080	100
	15	100		1620	125
	23	155		2160	150
	30	200		3240	200
			Linuron (Group 7)	195	75
				260	100
				520	200
				780	300
				1040	400

[†] Mallory-Smith and Retzinger 2003.

[α] Applied with MCPA ester 500 (Group 4) in a 1:84 ratio.

[β] Formulated as a single product in a 1:1 ratio.

[γ] Formulated as a single product in a 4.4:1:1 ratio.

Table 2.4 Response of field violet to herbicides applied to spring wheat at the 3- to 5-leaf stage in field experiments conducted at Lacombe and Lamont in 2002 and 2003.

	Control[α]				Biomass (dry)		Reproductive potential	
	2002		2003		2002	2003	2002	2003
Treatment	4 WAT	8 WAT	4 WAT	8 WAT	5 WAT		4 WAT	8 WAT
	%				g m^{-2}		RU plant^{-1}	
Bentazon	60	40	0	0	7	16	2	12
Glyphosate (PRE)[β]	–	–	90	80	–	0 *	–	2 *
Glyphosate + florasulam (PRE)[β]	–	–	90	90	–	1 *	–	1 *
Florasulam + MCPA Ester	10	10	0	0	6	21	3	13
Fluroxypyr + 2,4–D LV ester 600	90	90	70	80	4 *	7 *	2	2 *
Linuron	30	30	10	20	6	15	4	11
MCPA + mecoprop + dicamba	40	50	60	60	6 *	9 *	2	6 *
Metribuzin	50	30	40	50	3 *	3 *	2	7 *
Metsulfuron methyl	80	60	80	90	6 *	13 *	2	0 *
Sulfosulfuron	70	50	80	90	6 *	6 *	2	0 *
Thifensulfuron methyl + tribenuron methyl	60	50	80	80	2 *	12 *	2	1 *
Untreated control	0	0	0	0	9	23	3	13
SE[γ]	20		10		3	9	1	2
F-test[δ]	–		–		0.01	0.04	ns	<0.01

Biomass and reproductive potential data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Analyses were conducted with data from all treatments, but data from weed-free controls are not presented. Means of herbicide treatments followed by '*' are significantly different ($P < 0.05$) from untreated controls. Abbreviations: WAT, weeks after treatment; RU, reproductive units; PRE, pre-planting.

[α] Visual estimate of field violet control. Scale from 0 (no observed effect) to 100 (complete eradication), with benchmarks of 50 (suppression of growth) and 70 (agronomically acceptable control). No statistical comparisons to the untreated control were conducted on visual estimates of control.

[β] PRE applications were included in the experiment in 2003 only.

[γ] Standard error of the difference between least square means.

[δ] P-value for F-tests of the hypothesis that least square means of treatments are identical.

Table 2.5 Effects of herbicides on field violet density 4 and 8 weeks after treatment in field experiments conducted at Lacome and Lamont in 2002 and 2003.

	Field violet density					
	2002			2003		
Treatment	Initial	4 WAT	8 WAT	Initial	4 WAT	8 WAT
	No. m^{-2}					
Bentazon	40	15	25	35	80	25
Glyphosate (PRE)$^{\alpha}$	-	-	-	105	40 *	20 *
Glyphosate + florasulam (PRE)$^{\alpha}$	-	-	-	70	20 *	10 *
Florasulam + MCPA Ester	30	25	30	45	85	40
Fluroxypyr + 2,4–D LV ester 600	25	0 *	5 *	40	35 *	5 *
Linuron	30	20	30	50	70	25
MCPA + mecoprop + dicamba	35	20	10 *	30	50 *	15 *
Metribuzin	50	20	25	30	30 *	15 *
Metsulfuron methyl	40	10	10 *	60	15 *	5 *
Sulfosulfuron	40	21	25	35	15 *	5 *
Thifensulfuron methyl + tribenuron methyl	40	15	25	45	25 *	10 *
Untreated control	40	25	35	45	85	45
SE$^{\beta}$		11			15	
F-test$^{\gamma}$		0.02			<0.01	

Plant density data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Analyses were conducted with data from all treatments, but data from weed-free controls are not presented. Means of herbicide treatments followed by '*' are significantly different ($P < 0.05$) from untreated controls. Abbreviations: WAT, weeks after treatment; PRE, pre-planting.

[α] PRE applications were included in the experiment in 2003 only. Initial density for these treatments includes all weed stages.

[β] Standard error of the difference between least square means.

[γ] P-value for F-tests of the hypothesis that least square means of treatments are identical.

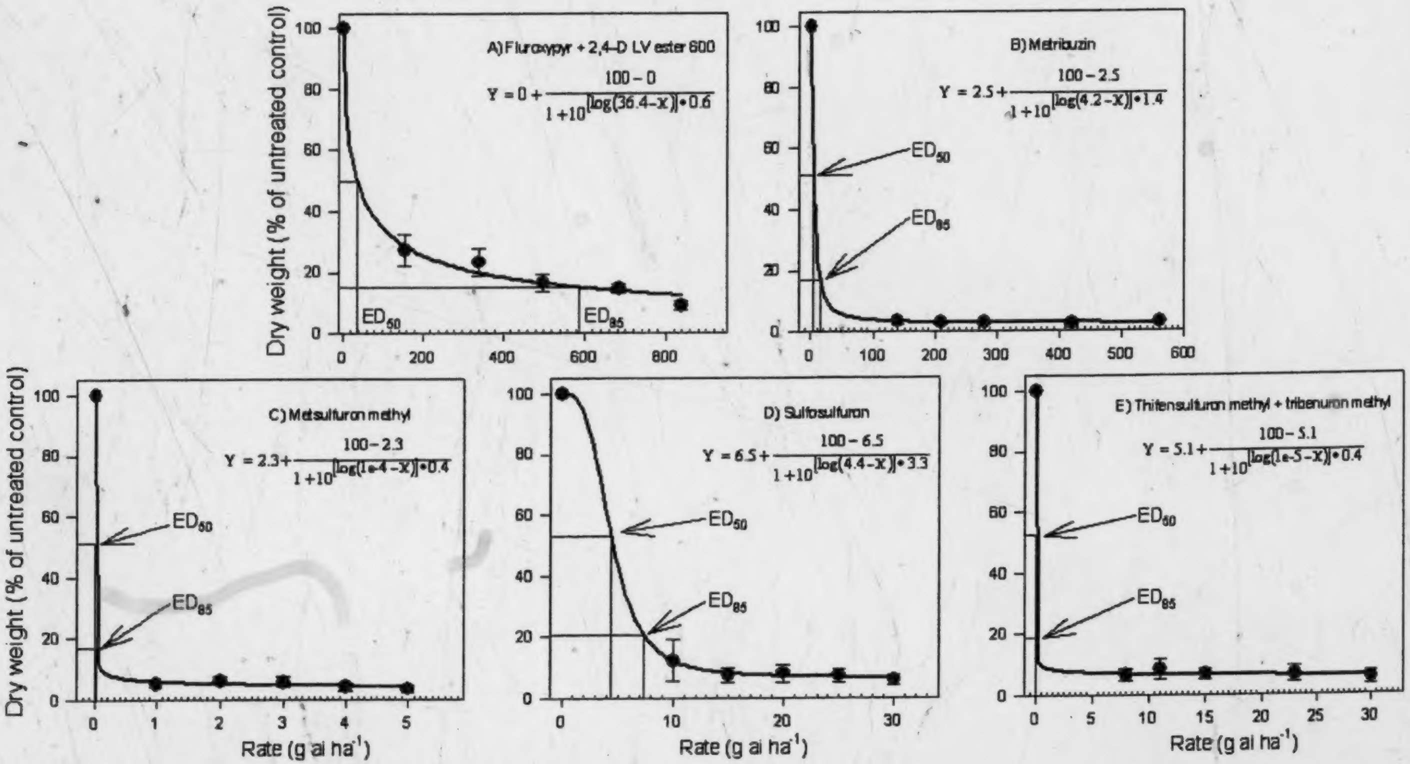

Figure 2.2 A–E. Dose response of field violet dry weight accumulation (4 WAT) to herbicides applied to plants at the 3- to 4-leaf stage in the greenhouse in 2003. Data are expressed as mean (spheres) +/- one standard error (bars, n = 4). Lines are plots of equations obtained from regression analyses and are significant at $P < 0.01$. Y and X in equations represent dry weight as a percent of the untreated control and herbicide rate in g ai ha^{-1}, respectively. ED_{50} and ED_{85} values are indicated by drop lines. Nonlinear analysis (PROC NLIN) was used to fit the data based on contrast F-tests reporting a significant ($P < 0.01$) nonlinear response of field violet biomass to herbicide rate.

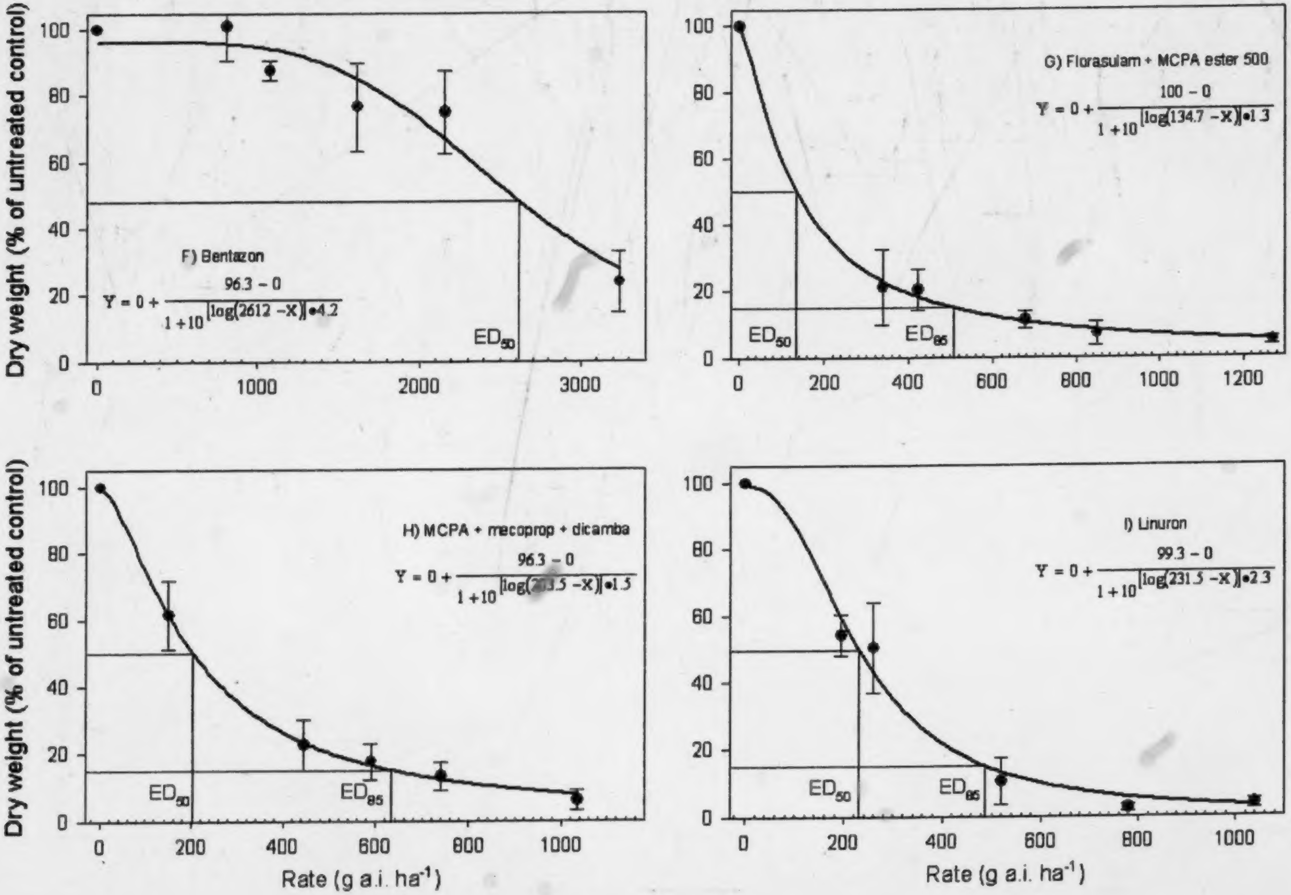

Figure 2.2 F–I. Dose response of field violet dry weight accumulation (4 WAT) to herbicides applied to plants at the 3- to 4-leaf stage in the greenhouse in 2003. Data are expressed as mean (spheres) +/- one standard error (bars, n = 4). Lines are plots of equations obtained from regression analyses and are significant at $P < 0.01$. Y and X in equations represent dry weight as a percent of the untreated control and herbicide rate in g ai ha^{-1}, respectively. ED_{50} and ED_{85} values are indicated by drop lines. Nonlinear analysis (PROC NLIN) was used to fit the data based on contrast F-tests reporting a significant ($P < 0.01$) nonlinear response of field violet biomass to herbicide rate.

Table 2.6 Effect of herbicides, applied to control field violet, on wheat biomass (dry) 5 WAT and seed yield at maturity, in experiments conducted at Lacombe and Lamont in 2002 and 2003.

Treatment	Crop biomass		Seed yield	
	2002	2003	2002	2003
	$g\ m^{-2}$		$t\ ha^{-1}$	
Bentazon	180	545	0.72	2.99
Glyphosate (PRE)[α]	-	580	-	3.02
Glyphosate + florasulam (PRE)[α]	-	595	-	3.19
Florasulam + MCPA Ester	195	550	0.66	3.09
Fluroxypyr + 2,4–D LV ester 600	175	525	0.60	2.80
Linuron	210	500	0.66	2.89
MCPA + mecoprop + dicamba	170	585	0.59	3.07
Metribuzin	190	600	0.69	3.49 *
Metsulfuron methyl	195	580	0.70	2.98
Sulfosulfuron	195	595	0.61	3.24
Thifensulfuron methyl + tribenuron methyl	210	575	0.69	3.14
Untreated control	205	550	0.71	3.00
Weed-free control	250 *	595	0.79	3.44
Se[β]	15	45	0.08	0.21
F-test[γ]	0.04	ns	ns	ns

Wheat biomass and seed yield data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Means of herbicide treatments followed by "*" are significantly different ($P < 0.05$) from untreated controls. Abbreviations: WAT, weeks after treatment; PRE, pre-planting.

[α] PRE applications were included in the experiment in 2003 only.

[β] Standard error of the difference between least square means.

[γ] P-value for F-tests of the hypothesis that least square means of treatments are identical.

2.6 References

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Chapter 3

Herbicidal management of field violet (*Viola arvensis* Murr.) in canola (*Brassica napus* L.)

3.1 Introduction

Field violet (*Viola arvensis* Murr.) is one of the most abundant weeds of grain crops in Europe (Hyvonen *et al.* 2003; Schroeder *et al.* 1993). It persists within disturbed environments due to phenotypic plasticity and variability in lifecycle (annual, winter annual, short-lived perennial) (Alex and Switzer 1976; Doohan and Monaco 1992; Kakes 1982). The weed is well-adapted to light and heavy-textured soils, the latter being preferred when moisture is limiting (Bachthaler *et al.* 1986). It is capable of colonizing both alkaline and acid soils, favoring soils of neutral pH (Bachthaler *et al.* 1986; Nordmeyer and Dunker 1999). Extended seed dormancy and oscillation between dormancy and non-dormancy allows field violet to germinate in flushes throughout the growing season (Baskin and Basin 1995; Odum 1965). Tillage has been observed to stimulate emergence (Doohan *et al.* 1991; Froud-Williams *et al.* 1984), however in western Canada the weed appears predominantly within reduced tillage fields.

Infestations of field violet have been identified in canola (*Brassica napus* L.) fields of western Canada. The 1997 Alberta Weed Survey (Thomas *et al.* 1998) identified a canola field in the Peace Lowland ecoregion having greater than 400 field violet plants m^{-2}. Similar infestations have been reported at various locations throughout western Canada (Doohan and Monaco 1992; Thomas *et al.* 1996). There is currently no information on herbicide alternatives for field violet in canola crops of western Canada.

Canola is one of the most common field crops in western Canada, covering a total of 3.8 million hectares in 2001(Statistics Canada 2002). Alberta, Manitoba and Saskatchewan cropped 1.1, 0.8 and 1.9 million hectares of canola, respectively. Herbicide-tolerant cultivars are widely grown, comprising 89 and 81% of the total canola produced in 2001 in Alberta and western Canada, respectively (Downey and Buth 2003; Leeson *et al.* 2002). Transgenic cultivars with resistance to Group 9 (glyphosate) and Group 10 (glufosinate ammonium) herbicides (Mallory-Smith and Retzinger 2003) comprised 49 and 20%, respectively, of the canola produced in Alberta in 2001 (Leeson *et al.* 2002). Imidazolinone-tolerant canola cultivars, which are non-transgenic and have resistance to the Group 2 (imidazolinone and sulfonylurea) herbicides, represented an additional 20% of total canola produced in 2001.

Spring canola yield losses attributable to competition with field violet have not been established in Canada. However, field violet has a winter annual lifecycle, which in direct-seeded fields would allow large perennated plants to compete with canola at the critical period of crop establishment, during which time canola is particularly sensitive to weed competition (Blackshaw *et al.* 1987; de St. Remy and O'Sullivan 1986; Forcella 1987; Marshall *et al.* 1989; Martin *et al.* 2001). In rapeseed crops of western Germany, where field violet comprises an average of 22% of weed biomass, it is considered to be the most economically significant weed (Bachthaler *et al.* 1986).

Previous reports indicate that control of field violet is highly variable with herbicides registered for use in conventional and herbicide tolerant canola. Clopyralid (200 g ai ha^{-1}) and surface applied trifluralin (1300 g ai ha^{-1}) did not control field violet (Doohan and Monaco 1992; Froment and Turley 1998). Imazethapyr (75 g ai ha^{-1}) had no effect on field violet when applied at the 6- to 8-leaf stage [Canadian Agricultural Services Coordinating Committee (CASCC) 1998]. Results with glufosinate ammonium are not consistent. With a single, fall-application of glufosinate ammonium (600 g ai ha^{-1}), Pilorgé and Mircovich (1999) observed no control of 4- to 6-leaf field violet in winter glufosinate-tolerant rapeseed plots in Thiverval-Grignon, France. Becker *et al.* (2001) reported the same result with glufosinate ammonium rates as high as 1200 g ai ha^{-1}. In contrast, a single 400 g ai ha^{-1} application of glufosinate ammonium (non-crop) suppressed 5- to 6-leaf plants in eastern Canada (CASCC 1998). Control with glyphosate in glyphosate-tolerant canola is possible, but the rate required may be greater than for most other dicotyledonous weeds. Pilorgé and Mircovich (1999) reported that field violet was poorly controlled by a post-emergence (POST) application of glyphosate at 720 g ae ha^{-1}, when other dicotyledonous weeds, such as shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.] and chickweed [*Stellaria media* (L.) Vill.], were fully controlled. In non-crop areas, field violet has been controlled with glyphosate at a rate 900 g ae ha^{-1} (CASCC 1998).

The primary objective of the present study was to evaluate the efficacy of post-emergence herbicides against field violet in conventional, imidazolinone-tolerant, glufosinate-tolerant and glyphosate-tolerant canola cultivars and management systems. A secondary objective was to determine the most effective time and rate of glyphosate application for control of field violet in glyphosate-tolerant canola.

3.2 Materials and Methods

3.2.1 Site Selection

Two commercial fields with established populations of field violet were identified in the Aspen Parkland ecoregion of Alberta and used for field trials in 2002 and 2003. Both fields were managed under a reduced-tillage regime (Doran and Smith 1987). Edaphic properties and soil fertility were determined from analysis[6] of a bulk sample of four soil cores, 6 cm diameter and 19 cm deep, from each site in the spring of 2002 and 2003. The first field was located northeast of Lamont, AB (53° 52' N 112° 39'W) in the Andrew Plain ecodistrict. The soil was a black solodized solonetz of the Camrose series (Alberta Soil Information Centre 2001) with a loam to sandy loam soil texture, a pH of 5.6–6 and 2.3–2.7% organic matter. It was 49–58, 30–38 and 12–14% sand, silt and clay, respectively. The second field was located northeast of Lacombe, AB (52° 32' N 113° 18'W) in the Pine Lake Upland ecodistrict. The soil was an orthic black chernozem of the Peace Hills series (Alberta Soil Information Centre 2001) with a sandy loam texture, a pH of 5.2–5.4 and 2.0–2.7% organic matter and was 64–66, 24–26 and 10% sand, silt and clay, respectively.

3.2.2 Field experiments

Experiments were situated at least 20 m from field boundaries on reasonably level ground with a relatively uniform density of field violet. In the second year of the study, experiments were moved to adjacent, non-overlapping locations within the same fields. Land used for experiments at the Lamont site in 2002 and 2003 was in barley (*Hordeum vulgare* L.) in the preceding year. At the Lacombe field site, the land used for experiments in 2002 and 2003 was in common oat (*Avena sativa* L.) and barley, respectively, in the preceding year.

To evaluate the efficacy of in-crop herbicides, four cultivars of canola, representing four different management systems, were planted into adjacent experiments, one cultivar per experiment. Cultivars were Q2 (conventional), Invigor 2663 (glufosinate-tolerant), 45A77 (imidazolinone-tolerant) and DKL34-55 (glyphosate-tolerant). An additional experiment was planted adjacent to the aforementioned experiments to evaluate the efficacy of various timings and rates of glyphosate, and was seeded to DKL34-55, a glyphosate-tolerant cultivar. All cultivars were seeded to a depth of 1.5–2 cm into rows 20.3 cm apart at a rate of 220–260 seeds m^{-2} using a minimal-disturbance air-seeder equipped with double-shoot, single side band openers and individual row packers. Individual plots were 8.5 m long, 2 m wide with six canola rows (Appendix C, Figure C.2.1). At seeding, nitrogen (100 kg N ha^{-1} as NH_4) was banded beneath seed rows to a depth of 8 cm; phosphorus (P_2O_5), potassium and sulfur (K_2SO_4) were deposited with the seed at rates of 25 kg P ha^{-1}, 60 kg K ha^{-1} and 20 kg S ha^{-1}, respectively.

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[6] Analysis performed by Norwest Labs, 7217 Roper Road, Edmonton, AB, Canada, T6B 3J4.

Each experiment was planted as a randomized complete block with four blocks; each block contained all herbicide treatments being evaluated (Table 3.1), as well as an untreated control and a herbicide standard consisting of a POST application of ethametsulfuron-methyl + sethoxydim (22 + 211 g ai ha^{-1}). Each block within the four in-crop herbicide experiments (Table 3.1, experiment numbers 1–4) also contained a weed-free control established by applying glyphosate at 1334 g ae ha^{-1} prior to crop seeding and maintained by hand roguing weeds as they emerged. Herbicide rates selected for experiments were chosen based on label recommendations outlined in the Alberta Crop Protection Guide (Ali 2003). For glyphosate, glufosinate ammonium and clopyralid, where a range of rates was permissible, the selected rate represented an intermediary value.

In-crop herbicides were applied when the canola plants were at the 2- to 5-leaf stage with a CO_2-pressurized self-propelled sprayer equipped with 11015 TeeJet[7] flat fan nozzles calibrated to deliver 100 L ha^{-1} at 207 kPa. Post-harvest and pre-seeding application timings were applied with a backpack sprayer, equipped with 11015 TeeJet flat fan nozzles, calibrated to deliver 100 L ha^{-1} at 152 kPa using CO_2 as a propellant. Herbicide application dates and corresponding weed stagings varied between locations and years (Table 3.2). A surfactant-petroleum hydrocarbon blend[8] was added to the ethametsulfuron-methyl + sethoxydim (herbicide standard), ethametsulfuron-methyl + quizalofop-p-ethyl, imazamox + imazethapyr and thifensulfuron methyl + quizalofop-p-ethyl spray solutions. Grass weeds were controlled prior to the 3- and 6-leaf stages in 2003 and 2002, respectively, with an application of sethoxydim (211 g ai ha^{-1}). Application of graminicide in 2002 was delayed to target a late flush of grass weeds. In Lamont in 2003, glyphosate-tolerant, imidazolinone-tolerant and glufosinate-tolerant canola cultivars were sprayed with clopyralid (202 g ai ha^{-1}) when the crop reached the 2-leaf stage to control a Canada thistle [*Cirsium arvense* (L.) Scop.] infestation. *Asteraceae*-family weeds were manually removed from the conventional canola cultivar to allow for evaluation of clopyralid as a treatment within the experiment.

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[7] Spraying Systems Co.,425 J Meyer Road, Uniontown, WA, 99179.

A visual estimate of field violet control, hereafter referred to as control, was evaluated 1, 2, 4 and 8 weeks after POST herbicide application (WAT) and rated on a 100 point scale (0 = no control, 100 = complete plant mortality). The fall (post-harvest) application was scored for control 3 WAT in Lamont in 2001 and 1 WAT in Lacombe and Lamont in 2002. Additional control ratings were not recorded from this treatment due to snow cover. Acceptable control of field violet was judged as a rating of ≥70% control 8 WAT and required that the majority of field violet plants were killed and that survivors had no or very little reproductive capability. Suppression of weed growth was denoted by a rating of 50–69% control. Weeds were non-destructively counted in two 0.25 m^2, randomly selected, quadrats within rows 2–5 of each plot, immediately following herbicide application, and 4 and 8 WAT. Counted weeds were categorized as either small (cotyledon to 4-leaf stage) or large (beyond the 4-leaf stage). Due to large fluctuations in the density of small weeds, only large weed density is presented. Canola plants were counted after they began to flower in two, randomly selected, 0.25 m^2 quadrats from within rows 2–5 of each plot. Crop and weed biomass samples were collected 5 WAT by harvesting all plants at ground level from three 0.25 m^2, randomly selected, quadrats within rows 2–5 of each plot. Biomass samples were subsequently placed in a dryer at 60 °C for 72 hours and weighed. Measurements of field violet height (ground to stem apex) and the number of reproductive units (flowers, dehisced and non-dehisced seed capsules) per plant were taken from a maximum of five and ten randomly selected plants per plot in 2003 and 2002, respectively, recorded 8 WAT in 2003 and, due to environmental conditions, 4 WAT in 2002. At crop maturity, all plots were desiccated with a foliar application of diquat (385 g ai ha^{-1}). Seven to ten days after desiccation a 7.1 m^2 portion of each plot was harvested with a straight-cut combine, dried thereafter at 60 °C for 72 hours, cleaned and the seed weight per plot and 1000-seed weight recorded.

All results were analyzed within mixed models, with locations and blocks considered random, and herbicide effects considered fixed (SAS Institute Inc. 1999). Year effects were initially included and considered fixed, but were ultimately analyzed separately due to heterogeneous error variances and significant year × herbicide interaction, both of which were presumably the result of extreme differences in precipitation between years (Figure 3.1). The denominator degrees of freedom used to calculate the significance of fixed effects were adjusted using the method outlined by Kenward and Roger (1997). Weed control and plant density data collected 2,

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[8] Merge™, 50% surfactant blend + 50% petroleum hydrocarbon solvent. BASF Canada, 345 Carlingview Drive, Toronto, ON, Canada, M9W 6N9.

4 and 8 WAT were combined and analyzed as repeated measures over time, allowing for error mean squares to be adjusted for covariance between temporal observations. In this model, location and block effects were again considered random, and herbicide, week (after herbicide application) and herbicide × week effects considered fixed. All quantitative data (crop and weed biomass, seed yield, weed plant density, weed height and weed reproductive potential) were square root transformed $[(x+1)^{0.5}]$ prior to analyses (Steel and Torrie 1980). Proportion data (relative weed biomass) were arcsine square root transformed. Transformations were conducted to normalize the distribution of residual error and reduce heteroscedasticity. Field violet plant density, biomass, relative biomass, height and reproductive potential in herbicide treated plots were compared to the untreated controls via orthogonal contrasts of transformed data (Steel and Torrie 1980). Additional contrasts of transformed data were used to compare canola seed yield, seed weight, plant density, and biomass in herbicide treated plots to both untreated and weed-free controls. Finally, another set of contrasts were derived to test for linear, quadratic or cubic responses of field violet biomass (transformed) to glyphosate rate (POST). When this response was found to be nonlinear, biomass data were fit to a four parameter log-logistic curve (Seefeldt *et al.* 1995) using the NLIN procedure of SAS (SAS Institute Inc., 1999). Linear responses were fit to a linear model using the REG procedure of SAS (SAS Institute Inc. 1999). Resultant models were used to estimate the glyphosate rate required to reduce field violet biomass by 50 (ED_{50}) and 85% (ED_{85}). To simplify interpretation of results, least square means of untransformed data are presented along with P-values and mean separations from transformed data (Tabachnick and Fidell 2001). Back-transformations were not conducted. Differences between herbicide treatments are considered significant when $P < 0.05$.

3.2.3 Greenhouse dose response assay

A dose response assay was conducted in the University of Alberta greenhouse in 2003. Seeds harvested from field violet plants growing in the Andrew Plain ecodistrict of Alberta were increased in the greenhouse in the winter and spring of 2002 and seeded into flats containing six, 13 × 18 cm trays of a soilless vermiculite-peat mixture (Metro-Mix 290[9]). Flats of plants were watered and placed in a greenhouse (16 hour photoperiod, 21 °C average temperature) until plants reached the 1- to 2-leaf, at which time they were thinned to 12 per tray. Each flat was an experimental unit. Flats of plants were sprayed at the 3- to 4-leaf stage (three weeks after planting) with herbicides and rates selected to verify data obtained from field experiments and to identify the rates required to cause 50 and 85% reductions in weed dry biomass (Table 3.3). Herbicides were applied with an indoor track sprayer outfitted with a low-drift air bubblejet nozzle[10], calibrated to apply 200 L ha^{-1} at 200 kPa. Following herbicide application, trays were returned to the greenhouse and irrigated from above as necessary. All trays were fertilized one week after herbicide application with 250 mL of a 1 g L^{-1} solution of 20:20:20 complete fertilizer. The entire experiment was repeated four times. There were therefore 30 herbicide treatments, with four blocks in time, and the experiment was considered a randomized complete block.

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[9] The Scott's Company, 14111 Scottslawn Road, Marysville, OH, USA, 43041.

Plants from each tray were counted and rated for control every seven days after herbicide application for 28 days. A nine-point rating scale (1–9) was used to score herbicide injury, with 1 representing no signs of herbicide injury and 9 representing 100% plant mortality. Immediately following the final scoring (28 days after application), plants were removed from trays at ground level and fresh weights recorded. Samples were dried for 24 hours in an oven at 60 °C and weighed to determine dry biomass.

Treatment effects were analyzed within mixed models with blocks in time considered a random effect and herbicide rate considered fixed. The denominator degrees of freedom used to calculate the significance of fixed effects were adjusted using the method outlined by Kenward and Roger (1997). Least square means of the biomass of field violet at each herbicide by dose combination are presented. Differences in least squares are discussed only when $P < 0.05$. Contrasts were derived to test for linear, quadratic or cubic responses of field violet biomass to herbicide rate. When this response was found to be nonlinear, biomass data were fit to a four parameter log-logistic curve as described above. Linear responses were fit to a linear model using the REG procedure of SAS (SAS Institute Inc. 1999). Models generated were used to determine ED_{50} and ED_{85} values and to calculate estimates of corresponding asymptotic standard errors.

3.3 Results and Discussion

3.3.1 Conventional canola

The three POST herbicides evaluated for use on the conventional canola cultivar (Q2) had no effect on field violet growth in field experiments (Table 3.4). In plots receiving an application of ethametsulfuron-methyl + quizalofop-p-ethyl or clopyralid, field violet comprised as much as 26 and 18% of total dry matter 5 WAT in 2002 and 2003, respectively (data not shown). Weed plant density in herbicide treated plots remained constant from initial to final counts (8 WAT) in 2002 ($\bar{x}$ = 51–78) and 2003 ($\bar{x}$ = 31–54) (data not shown). Tolerance of field violet to the herbicides employed in the field was verified in the greenhouse dose response assay. Clopyralid applied at rates of up to 600 g ai ha^{-1} had no significant effect on field violet growth (Figure 3.2A, Appendix C, Figure C.2.2). Ethametsulfuron-methyl reduced field violet biomass by 17% at the highest rate evaluated (45 g ai ha^{-1}), but the response to evaluated rates was not significant (Figure 3.2B).

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[10] ABJ Agri Products, 49 Cherry Crescent, Brandon, MB, Canada, R7B 0Y3.

Canola seed yield of herbicide treated plots in 2002 was 24–32% less than yield of plots kept weed-free (Table 3.5). In 2003, canola yields were greater and there were no significant ($P >$ 0.05) difference between treatments. Canola biomass 5 WAT did not differ between treatments in 2002 or 2003.

3.3.2 Glufosinate-tolerant canola

A single POST application of glufosinate ammonium (500 g ai ha^{-1}) did not provide consistent control of field violet. In 2002, this herbicide did not alter weed growth (Table 3.4). In 2003, weed density 8 WAT was 81% less than the density in the untreated control. Other measures of herbicide efficacy (weed biomass, relative biomass, height and reproductive potential) did not differ compared with untreated controls. Differential activity of glufosinate ammonium may have been the result of growing conditions at the time of herbicide application. Both locations experienced a severe drought in 2002 (Figure 3.1). Drought-tolerant field violet plants, quiescent due to the lack of moisture, were relatively unaffected by the herbicide and recovered rapidly following precipitation events in mid-July. Glufosinate ammonium inhibits the activity of an enzyme that is predominantly active when plants are undergoing photorespiration and N-assimilation (Wallsgrove *et al.* 1983). Drought- and other environmental stresses reportedly reduce photorespiration and limit phyotoxicity of this herbicide (Donn 1982; Petersen and Hurle 2001).

Soil moisture prior to herbicide application was adequate at both locations in 2003, but quickly became limiting at Lacombe, which received only 29 mm of rain in the six week period following herbicide application (Figure 3.1). Aggressively growing field violet plants at both locations were initially severely injured by application of glufosinate ammonium. In Lamont, rapid closure of the canola canopy following herbicide application negated weed recovery and resulted in a high level of control ($\bar{x}$ control 8 WAT = 86%, data not shown). In Lacombe, severe chlorosis of smaller weeds (< 8-leaf) led to their mortality, but moisture stress following herbicide application may have reduced competition from canola plants, as there was a decrease in the rate of canopy closure that allowed larger weeds to recover and resulted in a lower level of weed control ($\bar{x}$ control 8 WAT = 23%, data not shown).

The greenhouse dose response assay suggested that glufosinate ammonium provides reasonable control of small (3- to 4-leaf stage), actively growing field violet plants. Glufosinate ammonium caused substantial chlorosis and stunting at rates as low as 100 g ai ha^{-1} (Appendix C, Figure C.2.3) and reduced biomass 4 WAT by 50% (ED_{50}) at a rate of 364 g ai ha^{-1} (Figure 3.2C). However, field violet plants were able to recover from axial buds and compensated for mortality with vigorous growth of remaining plants, resulting in an extrapolated ED_{85} of 619 g ai ha^{-1} or 124% of the application rate used in field experiments. Madsen and Streibig (1999) reported substantially greater activity of glufosinate ammonium on 18-day old field violet plants in greenhouse experiments. They reported an 85% reduction in field violet fresh weight at an application rate of only 96 g ai ha^{-1}. However, they harvested plants at the point of maximum observed effect, and did not assess recovery from herbicide injury.

Increased activity of glufosinate ammonium in greenhouse experiments versus field experiments may have resulted from both a reduction in abiotic stresses that potentially antagonized weed growth and herbicide activity, and from the relative size of field violet plants at the time of application. Greenhouse plants were uniformly at the 2- to 4-leaf stage, while plants in field experiments were between the cotyledon and flowering stages. Pilorgé and Mircovich (1999) reported reduced efficacy of glufosinate ammonium on larger field violet plants. In their field studies, a dose of 600 g ai ha^{-1} controlled 2- to 4-leaf plants, but did not provide control of plants in the rosette stage. Additional herbicide efficacy in the present greenhouse experiments may have been the result of improved leaf coverage of the herbicide, due to the greater application volume used (200 L ha^{-1} vs. 100 L ha^{-1}) or the absence of crop debris preventing leaf contact. Etheridge *et al.* (2001) observed a slight increase in grass and broadleaf control with glufosinate ammonium when they increased application volume from 50 to 100 L ha^{-1}. They reported a similar increase resulting from the use of fan nozzles, which produce very small droplets (175 μm volume median diameter), over venturi-type nozzles that produce larger droplets (475 to 650 μm volume median diameter). Those authors noted that, given a constant application volume, doubling droplet size can reduce the number of droplets capable of contacting a surface by as much as 800%.

Application of glufosinate ammonium increased canola seed yield in 2003 by 23% over the untreated control, but did not significantly affect yield in 2002 (Table 3.5). Compared to the weed-free control, seed yield of glufosinate ammonium treated plots was not different in 2002 or

2003, but crop biomass was 11–19% less following application of this herbicide. This reduction in crop biomass 5 WAT may reflect some degree of transient glufosinate ammonium injury that did not affect crop yield. Similar finding have been reported on glufosinate-tolerant rice, where minor symptoms of glufosinate ammonium injury 14 and 35 DAT did not confer a yield reduction (Lanclos *et al.* 2003).

3.3.3 Imidazolinone-tolerant canola

Thifensulfuron methyl + quizalofop-p-ethyl (15+ 48 g ai ha^{-1}) provided good control of field violet in 2003 (Table 3.4). Weed density (8 WAT) and biomass (5 WAT) were 79 and 86% less, respectively, in plots receiving this herbicide than in untreated plots. Surviving field violet plants generally had a winter annual life cycle and were large (> 10-leaf) at the time of herbicide application. They underwent severe chlorosis and defoliation, similar to plants that died following application, but survived, entering into a quiescent state where they remained for most the growing season. As a result of impeded growth in this state, these plants produced an average of only one reproductive unit per plant (Table 3.4). Postemergence application of thifensulfuron methyl + quizalofop-p-ethyl was much less effective in 2002. Field violet growth was suppressed in experiments at Lacombe in 2002 ($\bar{x}$ control 8 WAT = 64%) and was not affected at Lamont ($\bar{x}$ control 8 WAT = 0%) (data not shown). Differential control was likely the result of growing conditions at the time of herbicide application. In 2002, many field violet plants were inactive at the time of herbicide application due to moisture stress. This phenomenon was more severe at Lamont than at Lacombe, possibly because the former site had substantially less early-season moisture from snow melt. Several researchers have observed reduced efficacy of foliage-applied Group two herbicides, such as thifensulfuron methyl, when soil moisture is limiting at the time of herbicide application (Bruce *et al.* 1996; Lundkvist 1997; Xie *et al.* 1997).

Imazamox + imazethapyr had little activity on field violet in field experiments. Treated plants underwent minor morphological changes, but growth was not affected. This herbicide did not reduce field violet plant density, height or reproductive potential in 2002 or 2003, however, it did reduce weed biomass in 2003 (Table 3.4). This reduction was likely the result of interference with canola, as weed biomass in this cultivar was inversely correlated to canola biomass ($R = -0.3$, $P < 0.01$, data not shown), which was greater in plots receiving this herbicide than in all other treatments, except for weed-free controls (Table 3.5). Poor control with imidazolinone-family herbicides has also been found in research conducted in eastern Canada, where imazethapyr, applied by itself to a non-crop infestation of field violet at 75 g ai ha^{-1}, had no effect on 6- to 8-leaf field violet plants (CASCC 1998).

Herbicide efficacy observed in field experiments was similar in the greenhouse dose response assay. The field violet biomass ED_{85} with thifensulfuron methyl was 7.9 g ai ha^{-1}, or 53% of the rate evaluated in field experiments (Figure 3.2D). The corresponding value with imazamox + imazethapyr could not be identified with experimental rates, although at the highest rate evaluated (30 g ai ha^{-1}), field violet biomass 4 WAT was 22% less than untreated controls (Figure 3.2E).

Canola biomass in thifensulfuron methyl treated plots was less than in weed-free controls in 2003 (Table 3.5). However, the cultivar used for experiments (45A77) was reportedly partially susceptible to this herbicide (Murray Hartman, Oilseed Specialist, Alberta Agriculture, Food and Rural Development, personal communication). The severe drought in 2002 masked the effects of this abnormality, but adequate growing conditions in 2003 allowed for full expression of susceptibility. The cultivar exhibited symptoms of Group 2 herbicide injury following application of thifensulfuron methyl, and maturity was delayed by approximately five to seven days (data not shown).

3.3.4 Glyphosate-tolerant canola

3.3.4.1 Postemergence

Glyphosate applied POST (445 g ae ha^{-1}) provided agronomically acceptable control of field violet. Plant density 8 WAT and biomass 5 WAT were reduced from untreated control values by 58 and 76%, respectively, in 2002, and by 85% in 2003 (Table 3.4). Formation of reproductive structures was almost completely inhibited by glyphosate application in 2003, as surviving plants produced an average of only 0.2 reproductive units per plant. Observed variation in control between different years was presumably the result of previously described differences in growing conditions at the time of herbicide application. As with other amino acid synthesis inhibiting herbicides, activity of glyphosate is reportedly greater on plants that are not suffering from drought-stress (Wicks *et al.* 1993; Wicks and Hanson 1995).

The response of field violet biomass to glyphosate rate was evaluated in field and greenhouse experiments. Estimated ED_{50} and ED_{85} coefficients from field experiments in 2002 were 345 and 567 g ae ha^{-1}, respectively (Figure 3.3A). Greater activity of glyphosate in 2003 reduced corresponding ED_{50} and ED_{85} values to 184 and 290 g ae ha^{-1}, respectively (Figure 3.3B). In the greenhouse, where application was made to actively growing plants at the 3- to 4-leaf stage, ED_{50}

and ED_{85} values were 273 and 360 g ae ha^{-1}, respectively. In a similar greenhouse experiment conducted in Denmark, Madsen and Streibig (1999) reported ED_{50} and ED_{85} values (fresh weight) of 300 and 1250 g ae ha^{-1}, when they harvested plants 12–13 days after application. Differences in ED_{85} may be explained by the harvest interval, as visual estimates of weed control taken weekly from our greenhouse experiments indicated that herbicide symptoms became progressively more severe from 2 WAT ($\bar{x} = 6.5$) to 4 WAT ($\bar{x} = 7.5$). Additionally, the authors of the Danish experiment noted a significant ($\alpha = 0.05$) lack of fit for the model used to calculate ED values for field violet, which may have resulted in exaggerated values.

In 2003, all rates of glyphosate, except for the highest application rate (1334 g ae ha^{-1}) resulted in increased seed yield over untreated controls (Table 3.6). Canola biomass was generally not influenced by glyphosate application; however, in 2003 biomass was 13% less in plots receiving the highest rate of glyphosate (1334 g ae ha^{-1}) than in untreated plots. Averaged over years, maximum canola biomass and seed yield was obtained with glyphosate at application rates of 222 and 445 g ae ha^{-1}. Following application of glyphosate at higher rates, canola appeared to be stunted, especially in 2003, which may have reduced crop biomass and yield in these plots.

3.3.4.2 Post-harvest and pre-plant

Post-harvest (FALL) and pre-seeding (PRE) applications of glyphosate effectively controlled field violet. Glyphosate applications applied FALL, PRE and FALL + PRE (445 g ai ha^{-1}) reduced field violet plant density in 2002 by 67, 97 and 99%, respectively, over untreated controls (Table 3.7). In 2003, plant density was not reduced in plots receiving FALL, PRE or FALL + PRE glyphosate application, possibly because precipitation events triggered flushes of field violet emergence subsequent to application and prior to canola crop establishment. Severe drought in 2002 likely reduced or eliminated field violet emergence following herbicide application.

Field violet biomass was reduced by FALL, PRE and FALL + PRE applications in 2002 and 2003 compared with untreated controls (Table 3.7). Reproductive potential was reduced only by PRE and FALL + PRE applications. Overall, field violet control with PRE glyphosate application, as measured through visual estimates of weed control, and quantitatively (plant density 8 WAT, biomass 5 WAT and reproductive units plant^{-1} 4 or 8 WAT), was equivalent ($P > 0.05$) to control with POST application at a rate of 1334 g ae ha^{-1} (Table 3.7). Using the same benchmarks, FALL application provided control equivalent to POST application at rates of 890 and 222 g ae ha^{-1} in 2002 and 2003, respectively. FALL + PRE application did not improve control of field violet, beyond the level attained with a single PRE application, in either year. The finding that field violet populations are not reduced as substantially by a single FALL application is in agreement with survey data from southern UK, where the abundance of field violet was found to be greater in fields with a history of herbicide use in the fall than in comparable fields with a history of spring or summer herbicide application (Ewald and Aebischer 1999). High levels of control following PRE application of glyphosate are likely a reflection of the susceptibility of young, actively growing field violet and the inability of surviving or newly emerged weeds to compete with established canola crops for water, nutrients and sunlight. The latter may be particularly detrimental as Fogelsfor (1973) has reported that rates of photosynthesis in field violet drop significantly when plants receive less than 53% of full sunlight. Success of post-harvest and preseed glyphosate applications has also been reported for other weakly competitive winter annual weeds, such as stinkweed (*Thlaspi arvense* L.) and common peppergrass (*Lepidium densiflorum* Schrad.) (Alberta Agriculture, Food and Rural Development 1999).

Glyphosate applied PRE and FALL + PRE increased seed yield of canola by 18–24 % over untreated controls in 2003 and crop biomass by 53–54% in 2002 (Table 3.6). FALL application alone resulted in no yield increase over untreated controls in 2003, but conferred a 30% improvement in 2002. Crop biomass was not affected by PRE, FALL or FALL + PRE applications of glyphosate in 2003. In both 2002 and 2003, PRE and FALL + PRE glyphosate applications conferred canola yield and biomass equivalent to, or better than, the best POST application rate. Post-harvest application alone was agronomically equivalent to the best POST application in 2002, but not in 2003, where seed yield was inferior.

3.4 Summary

Four site-years of data indicate that chemical control of field violet may be limited within some canola management systems. No POST herbicides evaluated provided control of field violet infestations in conventional canola. Results were more ambiguous in glufosinate-tolerant canola, but suggest that control with a single application of glufosinate ammonium at 500 g ai ha^{-1} is unacceptable unless the crop is competitive and able to close the canopy shortly after application. Field violet infestations in imidazolinone-tolerant canola can be controlled with an application of thifensulfuron-methyl, which should be timed to target young, actively growing field violet plants. In glyphosate-tolerant canola, glyphosate provided control of field violet at rates of 316–550 g ae ha^{-1}. Lower rates were effective when environmental conditions were optimal and weeds were predominantly small and actively growing. Higher rates were required when the converse was true.

Preemergence application of glyphosate (445 g ae ha^{-1}) provided excellent control of field violet and could be used as a management tool prior to planting a cultivar of canola where in-crop herbicides are not effective. The efficacy of this strategy would be improved by minimizing the period of time between herbicide application and establishment of a competitive stand of canola, and thereby shortening the interval during which late-emerging field violet could grow without crop competition. In Europe, an alternative strategy that has successfully controlled field violet is the utilization of PRE herbicides with residual activity, such as pre-plant incorporated trifluralin (420 g ai ha^{-1}) alone or in conjunction with PRE metolachlor (Froment and Turley 1998; Gummeson 1983).

In glyphosate-tolerant canola, cohorts of field violet emerging subsequent to PRE application could be controlled with an in-crop application of glyphosate, presumably at a low rate (< 445 g ae ha^{-1}) as most plants would be young and highly susceptible. A similar recommendation was made by Clayton *et al.* (2002) in a study examining the effect of glyphosate timing on canola yield. The authors found that canola yield following a PRE application of glyphosate was sub-optimal when large flushes of weeds emerged after application, and prior to the establishment of a competitive crop. They suggested the use of a second, in-crop application to reduce the negative effects of weed interference on crop yield.

Post-harvest glyphosate application (445 g ae ha^{-1}) was highly effective at controlling field violet plants present in the fall. This application could be used in exclusion if a PRE application is not possible, emergence in the spring is minimal and a residual population of field violet in-crop is tolerable. Using a FALL application in conjunction with PRE application is not necessary as it provides no additional control over a PRE application alone. However, in fields that are to be cropped to glyphosate-tolerant canola, following up a FALL application with a POST application would likely improve control of field violet.

When grown in competition with a natural weed community containing field violet, the crop production of glufosinate-tolerant, imidazolinone-tolerant and glyphosate-tolerant canola cultivars tended to be greatest in plots receiving POST application of glufosinate ammonium, imazamox + imazethapyr or glyphosate (222–445 g ae ha^{-1}). These herbicide treatments, with the exception of imazamox + imazethapyr, also conferred the greatest field violet control within each management system, suggesting that reducing or eliminating interference between canola and field violet is an important prerequisite to obtaining maximum yield. In glyphosate-tolerant canola, plots receiving PRE and FALL + PRE applications of glyphosate also out-yielded untreated controls, substantiating the assumption of the importance of field violet control and demonstrating the value of early weed removal to maximize canola yield (Clayton *et al.* 2002; de St. Remy and O' Sullivan 1986; Martin *et al.* 2001; O'Donovan 1992).

3.5 Tables and Figures

Table 3.1 Herbicides, rates and application timings evaluated in field violet control in canola experiments conducted at Lamont and Lacombe in 2002 and 2003.

Experiment number	Canola cultivar and management system	Herbicides evaluated	Rate	Application Timing(s)[a]
			— g ai ha^{-1} —	
1	Q2	Clopyralid	202	POST
	Conventional	Ethametsulfuron-methyl + quizalofop-p-ethyl	15 + 48	POST
2	Invigor 2663	Glufosinate ammonium	500	POST
	Glufosinate-tolerant			
3	45A77	Imazamox + imazethapyr	15 + 15	POST
	Imidazolinone-tolerant	Thifensulfuron methyl + quizalofop-p-ethyl	15 + 48	POST
4	DKL34-55	Glyphosate	445	POST
	Glyphosate-tolerant			
5	DKL34-55	Glyphosate	223	POST
	Glyphosate-tolerant		445	POST
			890	POST
			1334	POST
			445	FALL
			445	PRE
			445	FALL + PRE

[a] Abbreviations: POST, post-crop emergence; PRE, pre-planting; FALL, post-harvest

Table 3.2 Dates of herbicide applications and corresponding field violet stages at Lamont and Lacombe experiments conducted in canola in 2002 and 2003.

Site	Trial year	Date of crop seeding	Date of herbicide application			Weed stage at application		
			FALL	PRE	POST	FALL	PRE	POST
Lacombe	2002	May 24	-	May 23	June 24	-	Cot	Cot – 8 lf
	2003	May 15	October 18	April 30	June 16	Cot – large^a	Cot – 10 lf	Cot – 10 lf
Lamont	2002	May 17	October 15	May 06	June 21	Cot – large^a	Cot – 2 lf	Cot – large^a
	2003	May 14	October 19	May 01	June 12	4 lf – 10 lf	4 lf – 10 lf	Cot – 10 lf

[a] Large refers to mature plants with many branches and reproductive potential

Abbreviations: Cot, cotyledon; lf, leaf; POST, post-crop emergence; PRE, pre-planting; FALL, post-harvest

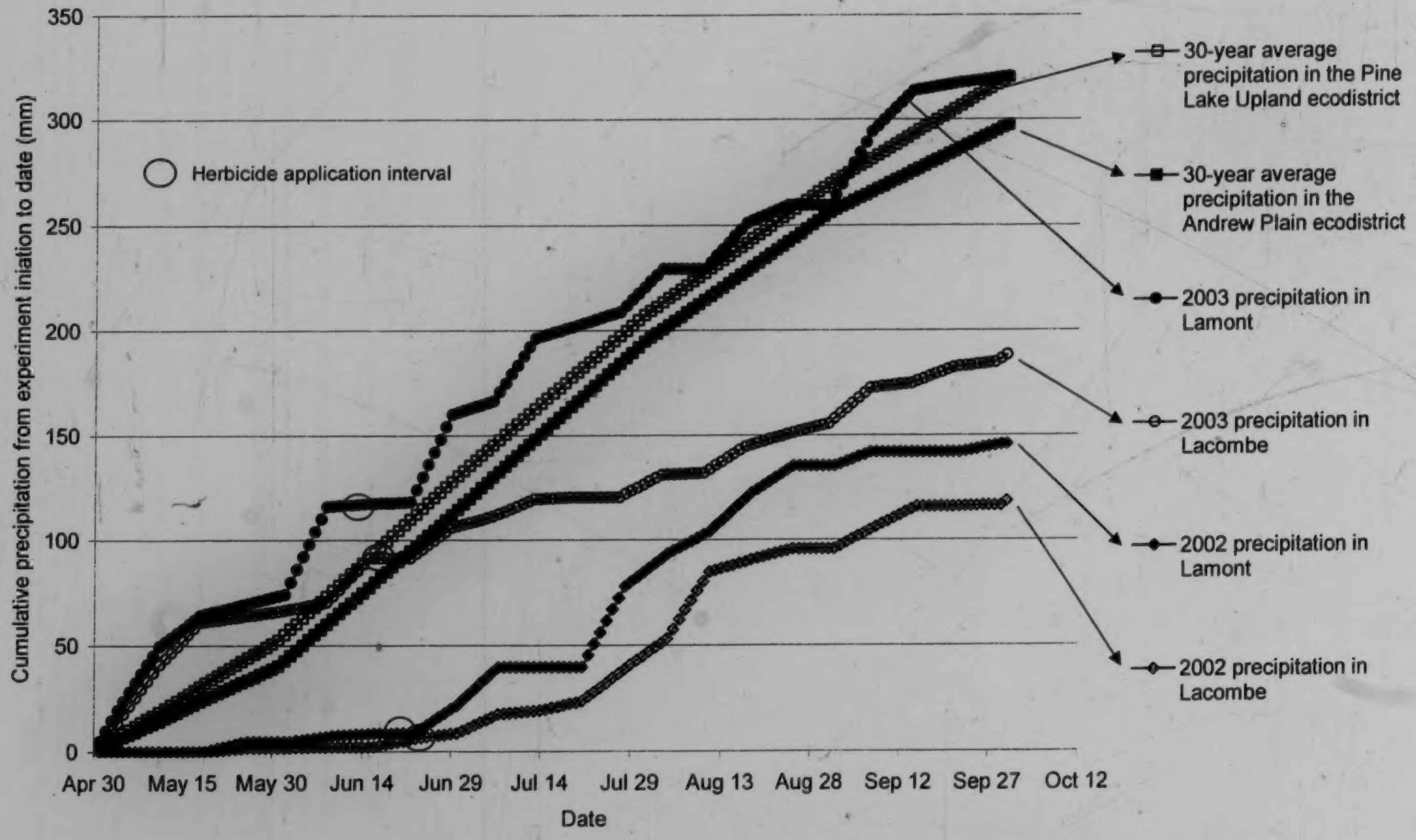

Figure 3.1 Cumulative precipitation for Lamont and Lacombe field violet sites in 2002 and 2003 versus the 30-year average for their respective ecodistricts (Andrew Plain and Pine Lake Upland).

Table 3.3 Herbicides and rates evaluated for control of field violet in the greenhouse in 2003.

Herbicide	Rate	Relative to rate used in field experiments
	— g ai ha^{-1} —	— % —
Clopyralid	100	50
	200	100
	300	150
	400	200
	600	300
Ethametsulfuron-methyl	11	75
	15	100
	23	150
	30	200
	45	300
Glufosinate ammonium	100	20
	200	40
	300	60
	400	80
	500	100
Imazamox + imazethapyr	4 + 4	50
	7.5 + 7.5	100
	11 + 11	150
	15 + 15	200
	22.5 + 22.5	300
Thifensulfuron methyl	8	50
	11	75
	15	100
	23	150
	30	200
Glyphosate	110	25
	225	50
	335	75
	445	100
	555	125

Table 3.4 Response of field violet to herbicides applied to canola plants at the 2- to 5-leaf stage in Lamont and Lacombe field experiments in 2002 and 2003.

Canola cultivar and management system	Treatment	2002						2003					
		Control[α]	Plant density	Biomass (dry)	Relative biomass[β]	Height	Reproductive potential	Control[α]	Plant density	Biomass (dry)	Relative biomass[β]	Height	Reproductive potential
		– % –	– No. m^{-2} –	– g m^{-2} –	– % –	– cm –	– RU plant^{-1}	– % –	– No. m^{-2} –	– g m^{-2} –	– % –	– cm –	– RU plant^{-1}
Q2	Clopyralid	0	55	23	10	9	4	0	55	37	6	27	17
Conventional	Ethametsulfuron-methyl + quizalofop-p-ethyl	0	70	19	10	9	7	0	45	38	6	26	17
	Ethametsulfuron-methyl + sethoxydim	0	80	15	9	9	5	0	50	33	8	27	16
	Untreated control	0	55	23	10	10	5	0	50	42	7	23	17
	SE[γ]	0	25	7	3	3	3	0	20	15	3	14	13
	F-test[δ]	ns	ns	ns	ns	ns	ns	<0.01	<0.01	ns	ns	0.01	<0.01
Invigor 2663	Glufosinate	10	75	11	5	9	4	55	10 *	12	2	11	9
Glufosinate-tolerant	Ethametsulfuron-methyl + sethoxydim	15	70	16	7	8	4	0	35	14	3	24	12
	Untreated control	0	45	12	6	9	5	0	55	17	3	24	15
	SE	10	25	5	2	4	2	15	15	7	2	11	6
	F-test	<0.01	ns	ns	ns	ns	ns	<0.01	0.01	ns	ns	ns	ns
45A77	Imazamox + imazethapyr	35	60	20	9	8	4	10	40	13 *	2 *	23	15
Imidazolinone-tolerant	Thifensulfuron methyl + quizalofop-p-ethyl	30	50	17	8	6	2	90	10 *	5 *	1 *	11	1 *
	Ethametsulfuron-methyl + sethoxydim	10	60	16	10	8	5	0	45	28	5	27	17
	Untreated control	0	70	19	9	9	5	0	45	33	6	28	13
	SE	15	30	10	5	4	2	5	15	9	2	14	4
	F-test	<0.01	ns	ns	ns	ns	ns	<0.01	<0.01	<0.01	<0.01	ns	0.02
DKL34-55	Glyphosate	70	45 *	7 *	3 *	6	2	95	5 *	2 *	0 *	9	0 *
Glyphosate-tolerant	Ethametsulfuron-methyl + sethoxydim	0	90	23	11	9	6	0	25	11	2	22	14
	Untreated control	0	105	28	12	10	6	0	30	15	3	26	15
	SE	10	25	5	2	3	2	5	10	4	1	12	3
	F-test	<0.01	0.02	0.03	0.02	ns	ns	<0.01	<0.01	0.03	0.03	ns	<0.01

Plant density, biomass, relative biomass and reproductive potential data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Analyses were conducted with data from all treatments, but data from weed-free controls are not presented. Means of herbicide treatments followed by '*' are significantly different ($P < 0.05$) from untreated controls. Visual control and plant density ratings were conducted 8 WAT, biomass and relative biomass were determined 5 WAT and weed height and reproductive were measured at 4 and 8 WAT in 2002 and 2003, respectively. Abbreviations: WAT, weeks after treatment; RU, reproductive units.

[α] Visual estimate of field violet control. Scale from 0 (no observed effect) to 100 (complete eradication), with benchmarks of 50 (suppression of growth) and 70 (agronomically acceptable control). No statistical comparisons to the untreated control were conducted on visual estimates of control.

[β] Calculated by the formula: relative biomass = biomass of field violet / (biomass of field violet + biomass of canola) .

[γ] Standard error of the difference between least square means.

[δ] P-value for F-tests of the hypothesis that least square means of treatments are identical.

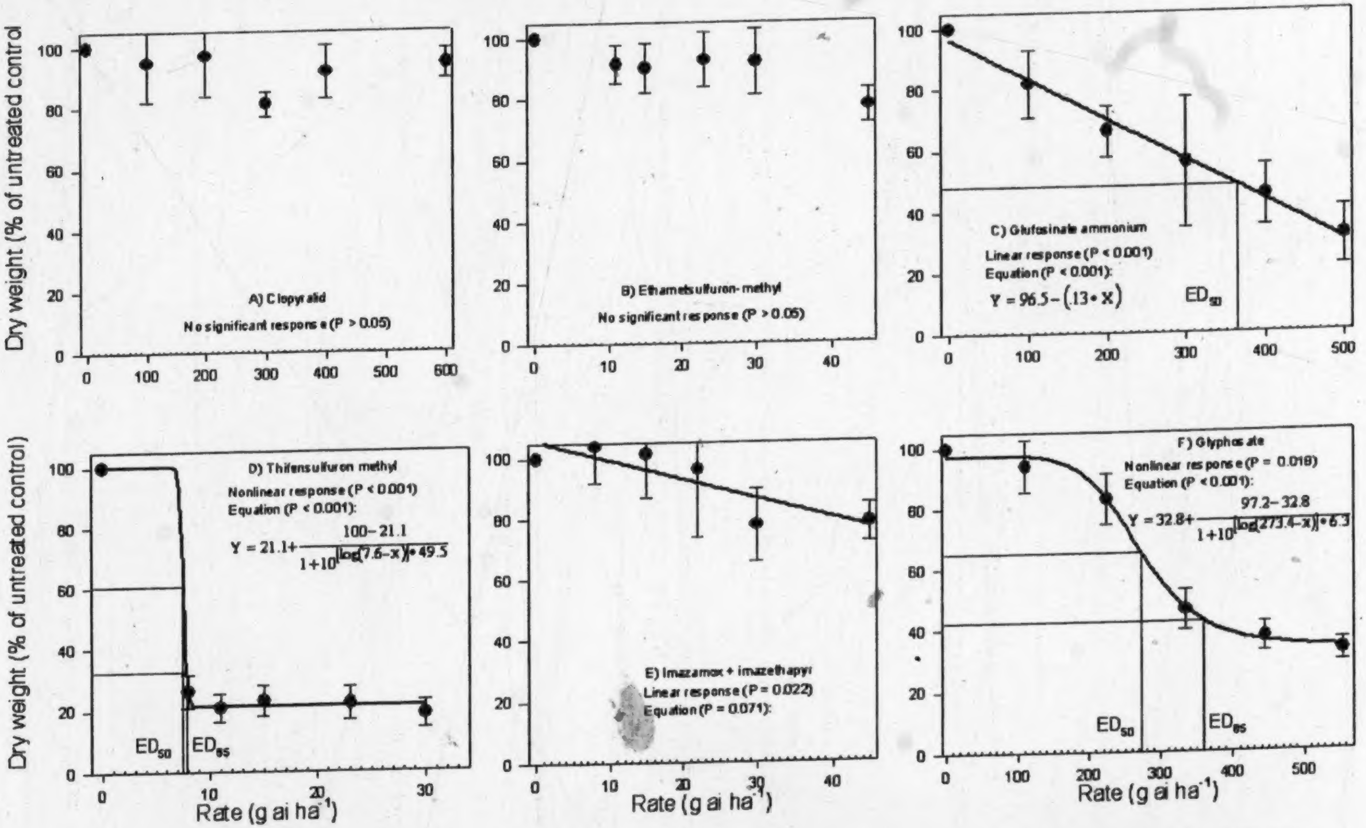

Figure 3.2 A–F. Dose response of field violet dry weight accumulation (4 WAT) to herbicides applied to plants at the 3- to 4-leaf stage in the greenhouse in 2003. Data are expressed as mean (spheres) +/- one standard error (bars, n = 4). Lines are plots of equations obtained from regression analyses. Y and X in equations represent dry weight as a percent of the untreated control and herbicide rate in g ai ha^{-1}, respectively. P-values of response curves are derived from single degree of freedom contrasts. P-values of equations are derived from nonlinear (PROC NLIN) or linear (PROC REG) regression analyses. ED^{50} and ED^{85} values are indicated by drop lines.

Table 3.5 Effect of herbicides, applied to control field violet, on canola biomass (dry) 5 WAT and seed yield at maturity, in experiments conducted at Lacombe and Lamont in 2002 and 2003.

Canola cultivar and management system	Treatment	Crop biomass		Seed yield	
		2002	2003	2002	2003
		—— $g\ m^{-2}$ ——		—— $t\ ha^{-1}$ ——	
Q2 Conventional	Clopyralid	200	475	0.98	1.73
	Ethametsulfuron-methyl + quizalofop-p-ethyl	175	530	0.88	1.92
	Ethametsulfuron-methyl + sethoxydim	165	480	0.91	1.86
	Weed-free control	220	540	1.29 *	2.08
	Untreated control	185	510	0.90	1.83
	SE[α]	30	50	0.11	0.13
	F-test[β]	ns	ns	<0.01	ns
Invigor 2663 Glufosinate-tolerant	Glufosinate	220	625	1.32	2.84 *
	Ethametsulfuron-methyl + sethoxydim	220	640	1.25	2.49
	Weed-free control	270 *	705 *	1.38	2.88 *
	Untreated control	190	590	1.13	2.30
	SE	15	35	0.16	0.17
	F-test	<0.01	<0.01	ns	<0.01
45A77 Imidazolinone-tolerant	Imazamox + imazethapyr	180	590 *	0.76	2.40
	Thifensulfuron methyl + quizalofop-p-ethyl	180	460	0.85	1.71
	Ethametsulfuron-methyl + sethoxydim	185	485	0.85	2.11
	Weed-free control	230	580 *	0.99 *	2.34
	Untreated control	185	475	0.75	2.02
	SE	20	30	0.10	0.25
	F-test	ns	<0.01	ns	ns
DKL34-55 Glyphosate-tolerant	Glyphosate (POST)	195	560	1.18	2.60
	Ethametsulfuron-methyl + sethoxydim	230	585	1.24	2.57
	Weed-free control	280 *	620	1.35 *	2.58
	Untreated control	230	545	1.06	2.36
	SE	20	45	0.12	0.26
	F-test	<0.01	ns	ns	ns

Crop biomass and seed yield data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Means of treatments followed by '*' are significantly different ($P < 0.05$) from untreated controls. Abbreviations: WAT, weeks after treatment.

[α] Standard error of the difference between least square means.

[β] P-value for F-tests of the hypothesis that least square means of treatments are identical.

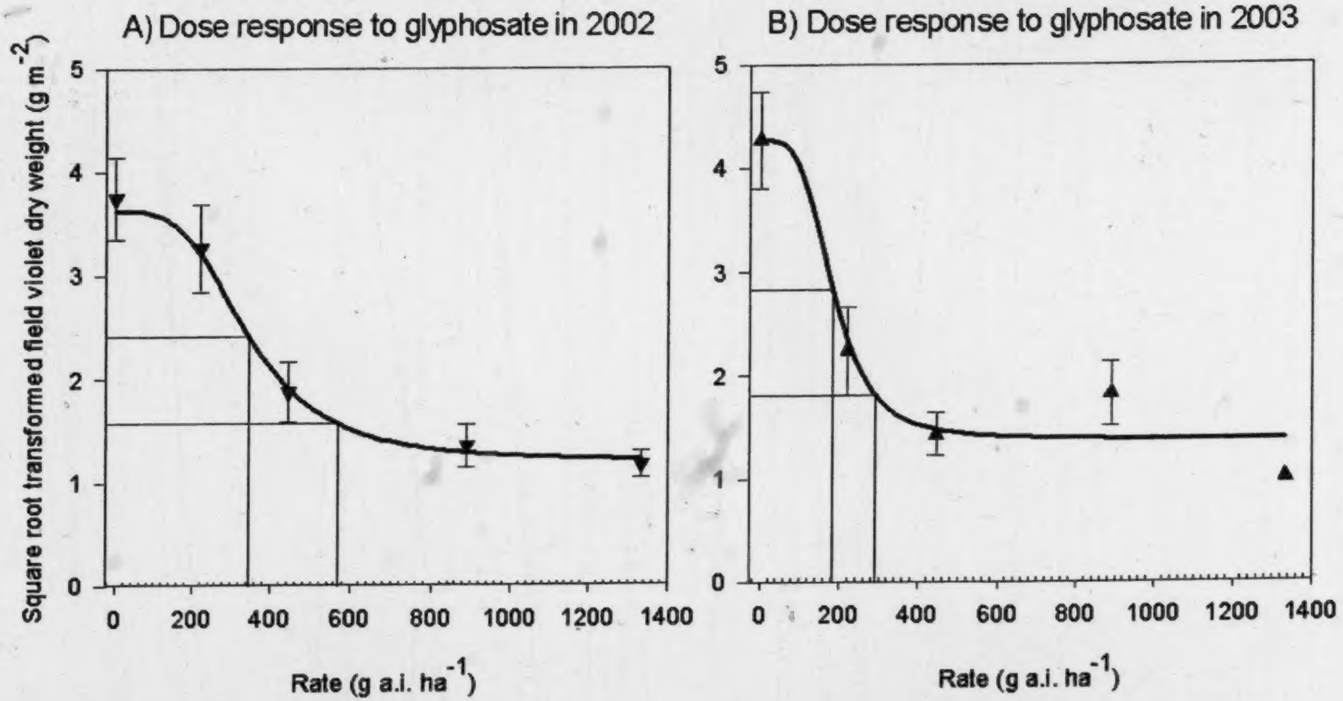

Figure 3.3 A–B. Dose response of field violet dry weight accumulation (5 WAT) to POST glyphosate applied to plants of all stages in field experiments conducted at Lamont and Lacombe in 2002 and 2003. Data are expressed as mean (triangles) +/- one standard error (bars, n = 22 – 24). Lines are plots of equations obtained from regression analyses. Y and X in equations represent transformed dry weight and herbicide rate in g ai ha^{-1}, respectively. P-values of response curves are derived from single degree of freedom contrasts. P-values of equations are derived from nonlinear (PROC NLIN) regression analyses. ED_{50} and ED_{85} values are indicated by drop lines.

Table 3.6 Effect of timing and rate of glyphosate application to control field violet, on canola biomass (dry) 5 WAT and seed yield at maturity, in experiments conducted at Lacombe and Lamont in 2002 and 2003.

	Crop biomass		Seed yield	
Treatment, rate and timing	2002	2003	2002	2003
	—— $g\ m^{-2}$ ——		— $t\ ha^{-1}$ —	
Glyphosate (445 g ha^{-1} FALL)	235	570	1.26 *	2.29
Glyphosate (445 g ha^{-1} PRE)	250 *	625	1.20	2.61 *
Glyphosate (445 g ha^{-1} FALL + PRE)	255 *	595	1.08	2.48 *
Glyphosate (222 g ha^{-1} POST)	215	565	1.16	2.72 *
Glyphosate (445 g ha^{-1} POST)	195	580	1.08	2.62 *
Glyphosate (890 g ha^{-1} POST)	195	535	1.13	2.57 *
Glyphosate (1335 g ha^{-1} POST)	190	495 *	1.19	2.41
Ethametsulfuron-methyl + sethoxydim	165	555	1.08	2.56 *
Untreated control	165	575	0.97	2.11
SE[α]	25	35	0.09	0.17
F-test[β]	ns	0.02	ns	0.01

Crop biomass and seed yield data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Means of treatments followed by '*' are significantly different ($P < 0.05$) from untreated controls.

[α] Standard error of the difference between least square means.

[β] P-value for F-tests of the hypothesis that least square means of treatments are identical.

Table 3.7 Response of field violet to glyphosate applied at various rates and timings in field experiments conducted at Lamont and Lacombe in 2002 and 2003.

	2002						2003					
Treatment, rate and timing	Control$^{\alpha}$	Plant density	Biomass (dry)	Relative biomass$^{\beta}$	Height	Reproductive potential	Control$^{\alpha}$	Plant density	Biomass (dry)	Relative biomass	Height	Reproductive potential
	– % –	- No. m^{-2} –	– g m^{-2} –	– % –	– cm –	– RU plant^{-1}	– % –	- No. m^{-2} –	– g m^{-2} –	– % –	– cm –	– RU plant^{-1}
Glyphosate 445 g ha^{-1} FALL	75	25 *	1 *	0 *	9	2	65	20	6 *	1 *	15	8
Glyphosate 445 g ha^{-1} PRE	90	5 *	0 *	0 *	6	0 *	75	15	3 *	0 *	15	5 *
Glyphosate 445 g ha^{-1} FALL + PRE	95	0 *	0 *	0 *	5	0 *	75	35	3 *	1 *	11 *	5 *
Glyphosate 222 g ha^{-1} POST	50	75	13	6	8	4	70	15	9 *	2 *	13	3 *
Glyphosate 445 g ha^{-1} POST	85	15 *	5 *	3 *	6	1 *	95	0 *	2 *	0 *	7 *	0 *
Glyphosate 890 g ha^{-1} POST	100	10 *	2 *	1 *	6	1 *	100	0 *	5 *	1 *	4 *	0 *
Glyphosate 1335 g ha^{-1} POST	100	0 *	1 *	1 *	0	0 *	100	0 *	0 *	0 *	0 *	0 *
Ethametsulfuron-methyl + sethoxydim	0	100	21	12	9	8	0	30	18 *	3 *	20	17
Untreated control	0	75	16	9	9	7	0	35	22	4	24	16
SE$^{\gamma}$	10	10	4	2	1	2	10	15	6	1	5	4
F-test$^{\delta}$	<0.01	<0.01	0.01	<0.01	ns	0.05	<0.01	ns	<0.01	<0.01	0.04	<0.01
Contrast F-tests:												
Linear response	<0.01	<0.01	<0.01	<0.01	ns	ns	<0.01	0.01	<0.01	<0.01	ns	ns
Quadratic response	<0.01	<0.01	ns	ns	0.02	0.01	<0.01	ns	<0.01	0.02	<0.01	<0.01
Cubic response	ns	ns	ns	ns	ns	ns	0.01	ns	<0.01	0.01	ns	ns

Plant density, biomass, relative biomass and reproductive potential data were tranformed (square root) prior to performing mean separations and F-tests. Untransformed least-square means and corresponding standard errors are presented. Analyses were conducted with data from all treatments, but data from weed-free controls are not presented. Means of herbicide treatments followed by "*" are significantly different ($P < 0.05$) from untreated controls. Visual control and plant density ratings were conducted 8 WAT, biomass and relative biomass were determined 5 WAT and weed height and reproductive were measured at 4 and 8 WAT in 2002 and 2003, respectively. Abbreviations: WAT,

[α] Visual estimate of field violet control. Scale from 0 (no observed effect) to 100 (complete eradication), with benchmarks of 50 (suppression of growth) and 70 (agronomically acceptable control). No statistical comparisons to the untreated control were conducted on visual estimates of control.

[β] Calculated by the formula: relative biomass = biomass of field violet / (biomass of field violet + biomass of canola) .

[γ] Standard error of the difference between least square means.

[δ] P-value for F-tests of the hypothesis that least square means of treatments are identical.

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Chapter 4

Biology of field violet (*Viola arvensis* Murr.) in Alberta: Implications for integrated weed management

4.1 Introduction

Knowledge of weed biology is essential for the development of effective integrated weed management strategies (Buhler *et al.* 2000; Holt 1994). In field crop production, important components of weed biology include phenology, generation time, relative fecundity and competitiveness. Phenological studies, relating to the interaction of climate with biological phenomena (i.e. germination, emergence, flowering), have been used to describe and predict emergence periodicity and thus optimal timing for management of several weed species (Ervio 1981; Grundy and Mead 2000). Knowledge of generation time and relative fecundity have been used to estimate inputs to the seedbank and relative staging of weed species with crop species (Buhler *et al.* 2000; Senseman and Oliver 1993). Weed competitiveness studies have resulted in the creation of plant density thresholds for a number of weed species (Bauer and Mortensen 1992; O'Donovan 1991; O'Donovan and Blackshaw 1997). The interaction of weed fecundity, generation interval and the relative timing of weed emergence often influence the interference potential of weeds with crops. For example, studies on the critical weed free periods in corn, canola and soybeans have shown that weeds emerging 3 to 5 weeks after crop emergence do not have a significant affect on crop yield, whereas those emerging before or with the crop can substantially reduce yield (Hall *et al.* 1992; Martin *et al.* 2001; Van Acker *et al.* 1993).

Field violet (*Viola arvensis* Murr.) is endemic to Europe, temperate west Asia and Africa, and has naturalized in agricultural systems of most other temperate regions (Holm *et al.* 1979; Wiersema and Leon 1999). It is reportedly increasing in overall abundance in field and horticultural crops of both Europe and North America, possibly due to herbicide tolerance and plasticity within disturbed environments (Bachthaler *et al.* 1986; Doohan and Monaco 1992; Hyvonen *et al.* 2003).

Extensive research has been conducted on the biology of native populations of field violet in Europe. Andreasen *et al.* (1991) studied the influence of edaphic factors on the occurrence of field violet in Denmark and reported an inverse relationship between its occurrence and the content of clay and exchangeable K within the soil. Ervio (1981) used regression analysis to find relationships between field violet emergence in Finland and various climatic factors. The author reported that peak emergence occurred in mid-June and mid-July and was dependent on high maximum temperature, low minimum temperature, rainfall and large diurnal temperature fluctuations. Other studies have outlined the habitat (i.e. Bachthaler *et al.* 1986; Wilson and Aebischer 1995), competitive ability (i.e. Semb 1996c; Fogelfors 1977), response to cultural practices (i.e. Grundy *et al.* 1995; Froud-Williams *et al.* 1984) and long-term population development of this weed in various crop rotations (i.e. Gerowitt and Bodendorfer 2001).

The biology of naturalized populations of field violet has been studied in the United States and eastern Canada (Baskin and Baskin 1995; Doohan *et al.* 1991; Doohan and Monaco 1992). To date there has been no research conducted on its biology in western Canada, where meteorological conditions and farming practices differ from other growing regions. Doohan and Monaco (1992) suggested that field violet has a preference for areas with high rainfall in North America. However, in the prairie ecoregions of western Canada, rainfall seldom exceeds 300 mm during the growing season ($\bar{x}$ = 192–356 mm) and soil moisture often limits plant development (Agriculture and Agri-Food Canada, 1999). Prairie ecoregions also often experience relatively harsh winters ($\bar{x}$ December to March temperature = -4.6 to -14.7 °C), which may affect overwintering of seeds and weed perennation. Heavy infestations of field violet have been identified within reduced tillage fields in Alberta. This contradicts previous reports from Europe and eastern Canada suggesting that field violet recruitment and establishment is much greater in tilled fields (Bachthaler *et al.* 1986; Doohan et al. 1991; Froud-Williams *et al.* 1984).

The objectives of the present research were fourfold: (1) to determine if there are differences in the biology (morphology, development, productivity) of populations of field violet from Europe and Alberta under a controlled environment; (2) to characterize emergence periodicity and phenology, plant development and lifecycle of this weed in spring wheat under a reduced tillage production system; (3) to quantify production losses of spring wheat and canola attributable to field violet in a natural weed flora; and (4) to investigate the effects of crop and cultivar selection on field violet growth and fecundity. Implications for weed management will also be discussed.

4.2 Materials and Methods

4.2.1 Morphology, development and reproductive potential of field violet in the greenhouse

A greenhouse experiment was conducted at the University of Alberta in 2003. Two seedlots of field violet were planted into two separate groups of 15 cm diameter pots filled with a soilless vermiculite-peat mixture (Metro-Mix 290[11]). The first seedlot was harvested from field violet plants growing in the Andrew Plain ecodistrict of Alberta (53° 52' N 112° 39' W) and increased in the greenhouse at the University of Alberta in the winter and spring of 2002. The second seedlot was obtained from the Herbiseed® company. It was second generation seed from plants originally growing naturally in a field near Wokingham, UK (51° 24' N, 0° 50' W), and subsequently increased in a field near Twyford, UK (51° 28' N, 0° 52' W). The first and second seedlots are henceforth referred to as 'domestic' and 'European', respectively. The experiment was designed as a randomized complete block with three blocks, one planted on each of three consecutive days. Each block consisted of 12 pots, six containing domestic seed and six with European seed (Appendix D, Figure D.2.1). Pots were watered and placed in a greenhouse with a 16 hour photoperiod and 21 °C average temperature until they reached the 2-leaf stage, at which time they were thinned to one plant per pot. Pots were watered as necessary and fertilized 5 weeks after planting, and every 3 weeks thereafter, with 500 mL of a 1 g L^{-1} solution of 20:20:20 complete fertilizer.

Growth staging of plants was recorded daily and quantified using the extended BBCH-scale (Hess *et al.* 1997) from the day of sowing (BBCH stage = 0) until all plants began to disperse mature seed (BBCH stage = 89). Selected morphological characters were measured: including width and length of cotyledons, lower and upper leaf blades (BBCH stage = 91) and the corolla, all of which were determined from 5–6 subsamples per plant. Additional measurements, determined from one sample per plant, included petiole length, stem length (BBCH stages = 69 and 92) and an earlier measure of lower leaf blade width and length (BBCH stage = 22). Reproductive potential of plants was determined by counting the number of seeds per capsule from 10 fully developed capsules per plant and the number of capsules per plant. This was destructively recorded by counting and removing dehisced capsules on a weekly basis for 26 weeks after planting (WAP). Total seed production was calculated as mean seeds per capsule × total capsule production. Following final pod counts (~180 days after planting (DAP)), plants were harvested at ground level and fresh weights recorded. Samples were then dried for 72 hours in an oven at 60 °C and reweighed to determine dry biomass and moisture content. Field violet seed weight was determined by bulking seed within blocks and weighing five, 200-seed subsamples from each bulked sample.

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[11] The Scott's Company, 14111 Scottslawn Road, Marysville, OH, USA, 43041.

All data were analyzed within mixed models where pots nested within blocks were considered a random effect and seedlot effects considered fixed. The denominator degrees of freedom used to calculate the significance of fixed effects were adjusted using the method outlined by Kenward and Roger (1997). Differences are discussed only when models are significant at $P < 0.05$. Where appropriate, descriptive analyses of the results are presented to indicate the minimum, maximum and average observed values.

4.2.2 Emergence periodicity and phenology of field violet in spring wheat

Experiments in 2002 and 2003 were conducted within the Aspen Parkland ecoregion of Alberta in commercial fields located northeast of both Lamont (53° 52' N 112° 39'W) and Lacombe (52° 32' N 113° 18'W), AB. Fields contained natural infestations of field violet and had a history of cereal and oilseed cropping under a reduced tillage management regime (Doran and Smith 1987). The soil at Lamont was a Black Solodized Solonetz, Camrose series (Alberta Soil Information Centre 2001) with 2.3–2.7% organic matter, a pH of 5.6–6 and 49–58, 30–38 and 12–14% sand, silt and clay, respectively. The soil at Lacombe was an Orthic Black Chernozem, Peace Hills series (Alberta Soil Information Centre 2001) with 2.0–2.7% organic matter, a pH of 5.2–5.4 and 64–66, 24–26 and 10% sand, silt and clay, respectively. Precipitation, air temperature and soil temperature at 2.5 and 10 cm were recorded using on-site data loggers[12] equipped with programmable sensors and rain gauges. Data collection began on May 6 and May 21 in Lamont and Lacombe, respectively, in 2002, and on April 24 in 2003.

The experiments were of a completely randomized design, with seven replications at each location. Each replication consisted of a 1 m^2 quadrat, randomly selected on May 14–24 from the center meter of a grid of 2 × 34 m rows, cited on level ground at least 20 m from the field perimeter (Appendix D, Figure D.2.2). Randomly chosen quadrats were eliminated and reselected if they had a population of more than 50 field violet plants m^{-2}. Immediately following quadrat selection, six rows of hard red spring wheat (cv. AC Barrie), spaced 20.3 cm apart, were seeded to a depth of 3–4 cm into the center meter of each grid row at a rate of 285–303 seeds m^{-2}, using a minimal-disturbance air-seeder equipped with double-shoot, single side band openers and individual row packers. Fertilizer was applied with seed and consisted of 100 kg N ha^{-1} as NH_4, placed 4–5 cm beneath seed rows, 25 kg P ha^{-1} (P_2O_5), 60 kg K ha^{-1} and 20 kg S ha^{-1} (K_2SO_4), placed with seed. Weeds other than field violet were removed by hand as they emerged to allow for direct comparisons to be made between quadrats. Wheat plants were harvested with a hand sickle to a height of 10–15 cm at seed maturity.

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[12] Wescor Environmental Products, 124 South 600 West, Logan, Utah, USA, 84321.

Newly emerged field violet plants in each quadrat were counted and tagged by placing a coloured aviary leg band (diameter: 14–19 mm) around the base of the plant. Band colour was changed weekly to allow weeds to be grouped into age categories. Field violet plant mortality within age categories was also recorded weekly and resulted in band removal. The growth stage of wheat plants and the least and most advanced field violet plant from each age category were recorded weekly and quantified using the extended BBCH-scale (Hess *et al.* 1997). Following development of reproductive structures on field violet plants, BBCH-staging was supplemented with counts of the number of branches, flowers, non-dehisced seed capsules and mature, dehisced seed capsules on each plant. Emergence, mortality and growth staging were recorded from one week after quadrat establishment until October 21, in 2002, and October 6, in 2003. No weed emergence was recorded in the initial week of the experiment because field violet plants within and adjacent to rows of wheat were displaced or buried by the process of seeding. To observe the growth habit of field violet, all age categories were allowed to overwinter in 2002 and in the following spring (April 24, 2003) the number of surviving weeds from each category recorded.

Field violet emergence data were analyzed within a mixed model, where week of emergence (WEEK) effects were considered fixed and replicates were considered random (SAS Institute Inc. 1999). Year and location were initially included in the model and considered fixed, but were ultimately analyzed separately due to heterogeneous error variances and significant interactions with WEEK effects, which may have been due to differences in weather conditions (Table 4.1). For analysis of the proportion of seven-day periods where field violet emerged and total emergence over the course of the experiment, year and location effects were considered fixed, and replicates were considered random. Correlation analyses were used to identify relationships between the occurrence and magnitude of weed emergence and meteorological variables summarized over the 7- and 14-day periods prior to the emergence event. A total of 18 variables were calculated from the meteorological data, of which 16 were related to soil and air temperature and two to rainfall. For this analysis, emergence and weather data from each year were separated into three time periods, early season (May 20 to June 30), mid-season (July 1 to August 31) and late-season (September 1 to experiment end), and correlated independently. To reduce the likelihood of making a type 1 error, a bonferroni adjustment ($P = \alpha \div C$, where P was equal to the significant p-value, α was equal to 0.05, and C was equal to 108, the number of variables to be tested) was used to identify significant correlations. Descriptive statistics were used to describe the growth staging of field violet and, where appropriate, the standard error of the mean (SEM) and sample size (n) are reported. The denominator degrees of freedom used to calculate the significance of fixed effects in all mixed models were adjusted using the method outlined by Kenward and Roger (1997). Least square means are presented for all data analyzed within mixed models. Differences between means are discussed when $P < 0.05$.

4.2.3 Competitiveness of field violet in wheat and canola

Field experiments were conducted to quantify interactions between a natural weed infestation containing field violet and spring-planted cultivars of wheat, conventional canola and herbicide-tolerant canola. Cultivars were planted into adjacent experiments, one cultivar per experiment. Spring wheat (cv. AC Barrie) was planted using rates and equipment as described above. Conventional canola (cv. Q2) and three herbicide-resistant canola cultivars (glufosinate-tolerant, Invigor 2663; glyphosate-tolerant, DKL34-55; imidazolinone-tolerant, 45A77) were seeded to a depth of 1.5–2 cm into rows 20.3 cm apart at a rate of 220–260 seeds m^{-2}, using seeding equipment and fertilizer rates as described previously.

Each experiment was planted as a randomized complete block with four blocks. Blocks consisted of 4–14, 8.5 × 2 m plots with 6 crop rows enclosed on both sides by a row of winter wheat. All but two of the plots within each block received a herbicide treatment as part of a concurrently running experiment and were disregarded for the present study. The two remaining plots consisted of a ‘weedy’ treatment, where dicotyledonous weeds were left unmanaged, and a weed-free treatment established by applying glyphosate (1334 g ae ha^{-1}) prior to crop seeding and maintained by hand roguing weeds as they emerged. The weedy treatment contained a natural weed flora with the exception of the removal, when necessary, of dandelion (*Taraxacum officinale* G. H. Weber ex Wiggers), Canada thistle [*Cirsium arvense* (L.) Scop.] and *Poaceae*-family weeds. The former two weed species were controlled by application of clopyralid (202 g ai ha^{-1}). The latter group of weeds was controlled prior to the 6- and 3-leaf stages in 2002 and 2003, respectively, by application of sethoxydim (211 g ai ha^{-1}) in canola and clodinafop-propargyl (56 g ai ha^{-1}) in wheat. Graminicide application in 2002 was delayed to target a late cohort of grass weeds.

The density of small (cotyledon to 4-leaf stage) and large (beyond the 4-leaf stage) field violet plants within the weedy treatment were determined from non-destructive counts of two 0.25 m^2, randomly selected quadrats, within crop rows 2–5 prior to crop seeding, at the 2- to 5-leaf stage of respective crops (~ 35 DAP), at anthesis (~55 DAP) and at the soft-dough / pod filling stage (~85 DAP). All other weed species were counted only once, ~35 DAP in 2002 and ~85 DAP in 2003. Measurements of field violet height (ground to stem apex) and the number of reproductive units (flowers, dehisced and non-dehisced seed capsules) per plant were taken from a maximum of five and ten randomly selected plants per plot in 2003 and 2002, respectively, recorded ~85 DAP in 2003 and, due to environmental conditions, ~55 DAP in 2002. In both treatments, canola and wheat plants were counted after anthesis/flowering had began (BBCH $\geq$ 65) in two, randomly selected, 0.25 m^2 quadrats from within crop rows 2–5 of each plot. Crop and weed biomass were sampled after anthesis (~60 DAP) by harvesting all plants at ground level from three 0.25 m^2, randomly selected quadrats within rows 2–5 of each plot. Biomass samples were subsequently placed in a dryer at 60 °C for 72 hours and weighed. Relative biomass of field violet was determined by calculating the weed's proportion of total sample biomass (crop biomass + field violet biomass). At crop maturity, both treatments were desiccated with a foliar application of diquat (385 g ai ha^{-1}). Seven to ten days after desiccation a 7.1 m^2 portion of each treatment was harvested with a straight-cut plot combine, dried thereafter at 60 °C for 72 hours, cleaned and the seed weight per plot and 1000-seed weight were determined.

Quantitative data, including crop biomass, seed yield, weed plant density, weed height and weed reproductive potential, were square root $[(x+1)^{0.5}]$ transformed prior to analysis in response to non-normal distribution of residual error and heteroscedasticity (Steel and Torrie 1980). Mixed models were used to analyze all results, where locations and blocks were considered random effects and treatment effects were considered fixed (SAS Institute Inc. 1999). Years were analyzed separately due to heterogeneous error variances, which may have been the result of differences in precipitation between years (Table 4.1). Regression analysis was used to test for linear dependence of crop yield and biomass on various measures of field violet abundance (plant density, biomass and relative biomass). R-square coefficients derived from significant ($P < 0.10$) regression models were used to estimate the proportion of crop yield and/or biomass reduction attributable to the presence of field violet. To determine the influence of crop and cultivar selection on weed growth and fecundity, field violet plant density, biomass, height and reproductive potential data from weedy plots were analyzed in separate mixed models where the cultivars were considered fixed and location and block effects were considered random. Orthogonal contrasts (Steel and Torrie 1980) were employed to compare wheat with canola and each canola cultivar to the rest. The denominator degrees of freedom used to calculate the significance of fixed effects in all mixed models were adjusted using the method outlined by Kenward and Roger (1997). Least square means of untransformed data are presented throughout for clarity, but P-values and mean separations are derived from transformed data models. Back-transformations were not conducted. Differences between treatments are considered significant when $P < 0.05$, unless otherwise noted.

4.3 Results and Discussion

4.3.1 Morphology and reproductive potential of field violet in the greenhouse

Cotyledons, lower leaves, petioles and the corolla of domestic field violet plants grown in the greenhouse were 20 to 140% larger than those of plants described in the northeastern United States and eastern Canada (Doohan and Monaco 1992; Gleason and Cronquist 1991) (Table 4.2). Upper leaves and stems were within previously documented ranges. Differences could be due to a plastic response to the photoperiod, light and temperature conditions in the greenhouse, or could be the result of differences in plant stage at the time of measurement. It should be noted, however, that upper and lower leaves became increasingly dimorphic following the final set of measurements taken, with upper leaves tending to become longer and more slender than lower leaves, as has been previously reported (Doohan and Monaco 1992). Fresh weight, dry weight and percent water content of field violet have not previously been documented at this growth stage.

Average seed production of field violet under controlled conditions is within the range reported by Doohan and Monaco (1992) in Nova Scotia (Table 4.3). Total estimated seed production ranged from 30,000 to 52,000 seeds per plant, with a mean of 40,000. Plants produced 24% of this total in the first 15 WAP and the remainder in the final 11 weeks of the experiment. Thousand seed weight was an average of 0.77 g.

European plants were very similar to domestic plants with respect to most morphological characters (Table 4.2). Cotyledons, petioles and stems were the same size on both domestic and European plants. Upper and lower leaf blades were slightly narrower on plants grown from domestic seed, but were of similar length. The corolla on domestic plants was 1 mm narrower and 2 mm shorter than the corolla on European plants. Visually, plants were of similar appearance, although petals on European plants were often more brilliantly coloured, containing deep purple and bright yellow colourations that domestic plants did not. Fresh weight, dry weight and water content did not differ between seedlots. Total estimated seed production also did not differ (Table 4.3), although mature pods from European plants contained as few as 6 seeds per capsule, whereas the minimum from domestic plants was twice that value. Maximum estimated seed production from European plants was 27% more than the maximum production from domestic plants and 44% more than the maximum documented seed production (Doohan and Monaco 1992).

4.3.2 Lifecycle of field violet in Alberta

The natural field violet population present in field experiments had three growth habits: annual, winter annual and short-lived perennial. Winter annual plants emerged in summer or fall, perennated over winter as rosettes, flowered the following growing season and generally died following a killing frost in the fall (data not shown). Annual and perennial plants emerged in spring or summer and flowered during summer and early-fall. Annual plants died in the fall along with winter annual plants, while perennials overwintered, began to flower the following spring and generally died in late-summer or fall. We did not observe perennials surviving through more than two growing seasons. The perennial growth habit of field violet has been observed in Ontario (Alex and Switzer 1976), but has not been reported in populations elsewhere (Doohan and Monaco 1992; Whitson *et al*. 1992).

4.3.3 Periodicity and phenology of field violet emergence in spring wheat

Field violet emergence occurred intermittently throughout the growing season in both years of the experiment (Figure 4.1). Emergence was summarized over 7-day periods beginning on May 19–20 and ending no earlier than October 8. Over that time, the proportion of 7-day periods during which the weed emerged were 0.60 and 0.69 (SEM = 0.02, n = 14) in 2002 and 2003, respectively. Periods of maximum emergence varied with year and location. Peak emergence occurred in mid-August in 2002 and corresponded to a period of no emergence in 2003. Emergence peaks for Lamont and Lacombe in 2003 occurred in early July and early October, respectively. In all site • years of the experiment there were periods of peak emergence in early June and September. Observations of field violet emergence in other temperate climates, have generally reported peaks of emergence in spring through early summer and again in the fall, with a period of little to no emergence in mid-summer (Doohan *et al*. 1991; Hakansson 1983; Roberts and Feast 1972).

Emergence was generally associated with meteorological variables 7 and 14 days before emergence (DBE). Emergence of field violet in Sweden was also reported to be dependent on meteorological events 14 DBE (Ervio 1981). Studies have suggested that lag periods of at least 7 days are important when studying the phenology of emergence due to the length of time required for germination and preemergence growth (Grundy and Mead 2000; Vleeshouwers 1997). In the present study, early season emergence was not consistently linked to any meteorological variables. In 2002, emergence occurred earlier in this period, when moisture from snow melt was still present and temperatures were cooler, resulting in inverse correlations between field violet emergence and temperature (Table 4.4). In 2003, rainfall was adequate and emergence increased during this period (Figure 4.3), resulting in positive correlations between emergence and temperature, which were only significant for soil temperature at a depth of 10 cm. Rainfall and low temperatures became important for mid-season emergence. In 2002, neither location received more than 15 mm of rain over a 7-day period until early-July and consequently, moisture became the limiting factor for germination and emergence (Figure 4.2). A cool, moist August allowed field violet to emerge abundantly and led to positive correlations with rainfall and negative correlations with most temperature variables. This inverse correlation with temperature was even stronger in 2003 (Table 4.4), when there was negligible emergence during the hottest period from late-July to the end of August, despite adequate rainfall. Late-season emergence was again not consistently linked to any meteorological variables. In 2002 it tended to be greater in early-September, when temperatures were warmer, which resulted in positive correlations with temperature. In 2003, high temperature continued to be restrictive and thus emergence generally increased from early-September into October as the temperature decreased.

When data from both locations were combined, emergence of field violet in 2002 was greatest (≥ 1 plant m^{-2} day^{-1}) when the period 14 DBE was characterized by rainfall accumulation of 21 mm (SEM = 1.5, n = 118), soil temperature at 2.5 cm of 15 °C (SEM = 0.3, n = 118), a difference between maximum and minimum daily temperature of 18 °C (SEM = 0.3, n = 118) and average maximum, minimum and mean air temperature of 23, 5, and 14 °C (SEM = 0.4, 0.3, 0.3, n =118), respectively. In 2003, the period 14 DBE was characterized by rainfall of 25 mm (SEM = 1.6, n = 97), soil temperature at 2.5 cm of 14 °C (SEM = 0.3, n = 97), a difference between maximum and minimum daily temperature of 13 °C (SEM = 0.2, n = 97) and average maximum, minimum and mean air temperature of 20, 7, and 13 °C (SEM = 0.4, 0.3, 0.3, n =118), respectively. Field violet did not emerge in 2003 when the average maximum and minimum temperatures 14 DBE were greater than 24 and 10 °C, respectively. In 2002, field violet emerged when minimum temperatures 14 DBE ranged from an average of -6 to 12 °C and maximum temperatures ranged from an average of 10 to 32 °C.

Phenology of field violet in 2003 was similar to that reported in the literature, with high temperatures suppressing both germination and emergence (Doohan *et al.* 1991; Hakansson 1983). Baskin and Baskin (2001) suggested that, as facultative winter annuals such as field violet lose dormancy, they first gain the capacity to germinate at low temperatures, and can only germinate at high temperatures following the complete loss of dormancy. The pattern of field violet emergence in 2002 may have been abnormal due to a lack of soil moisture. Emergence in that year was delayed until substantial rainfall occurred, after which weeds emerged independent of temperature. Bond and Baker (1990) reported similar results during a drought year in the UK, when they could not stimulate weed emergence through seedbed tillage until after a rain. Overall, results suggest that emergence of field violet is highly plastic and not readily predictable based on any single meteorological variable, but rather is a reflection of the complexity of intrinsic seed dormancy and the interaction between the effects of numerous weather variables.

Despite dry conditions, total field violet emergence during the period from May 20 to October 8 was greater ($P < 0.05$) in 2002 ($\bar{x} = 531$ plants m^{-2}, SEM = 80, range = 160–1113, n = 14) than in 2003 ($\bar{x} = 291$ plants m^{-2}, SEM = 47, range 52–668, n = 14). This finding was contrary to expected results, given that emergence is dependent on rainfall (Bachthaler *et al.* 1986; Ervio 1981). It is possible that reduced competition from drought-stressed wheat plants in 2002 may have provided less canopy closure and enabled field violet to better utilize available soil moisture. Several authors have reported that field violet density is greater under dry conditions, when the growth of competitors is impeded (Bachthaler *et al.* 1986; Mukula *et al.* 1969). An alternative explanation is that a greater portion of field violet seeds in the seedbank in 2003 were dormant. Baskin and Baskin (1995) reported that a maximum of 10% of seeds collected from field violet plants receiving less than 5 cm of moisture in the 2 weeks preceding seed collection germinated the following spring. When moisture was 6 cm or greater, seed germination was in the range of 35 to 100% in that study. Rainfall accumulation during a 14 day-period in the present study was > 5 cm only once in 2002 at Lamont, and never > 5 cm at Lacombe in 2002.

4.3.4 Growth staging of field violet in-crop and under greenhouse conditions

Field violet developed rapidly in spring wheat when environmental conditions were conducive for growth. In 2003, plants advanced to the rosette stage as fast as 1 week after emergence (WAE) (Figure 4.4). Flowering occurred at both locations in 2003 as few as 3 WAE and was followed by capsule production at 4 WAE, and mature seed production at 7 WAE. The growth rate of field violet was lower in 2002, possibly in response to moisture stress caused by insufficient rainfall (Table 4.1). At both locations in 2002, reproductive development began 5 WAE and seed capsules appeared 7 WAE. Release of mature seed was delayed until 10 WAE in Lacombe and 12 WAE in Lamont (data not shown).

Field violet plants with a winter annual life cycle are capable of developing much faster than summer annuals. Following a mild winter at Lamont, winter annual plants were observed at the flowering stage by late-April to early-May (data not shown). Winter annuals began to flower as early as 3 weeks after crop sowing, or 2 weeks after experiment initiation, in 2003, and in as few as 4 weeks after crop sowing in 2002 (data not shown). Dispersal of mature seed from these plants began 8 weeks after crop sowing.

Under adverse environmental conditions field violet growth ceased. On larger plants, leaves would often fold downward towards the stem and, if conditions did not improve, defoliation would follow. This quiescent state was generally triggered by heat and / or drought stress. Plants were capable of persisting for extended periods of time in this phase of arrested development. Five weeks after emerging in 2002, many field violet plants had not progressed beyond the 1-leaf stage (Figure 4.4). At Lacombe in 2003, 9 and 16 week old plants had not progressed beyond the 1- and 5-leaf stages, respectively (data not shown). The rosette stage of field violet was particularly persistent. Plants 18–19 weeks-old had not advanced beyond this stage (Figure 4.4). Lengthy persistence of plants in Lacombe in 2003 may have been due to precipitation. Early season (May to mid-June) rainfall was above average at Lacombe in 2003, but was poor in July and August (Table 4.1). Field violet plants that germinated and established under conditions of adequate moisture may have become drought-stressed and entered into a quiescent state, where they remained until moisture improved. Further, good early season moisture allowed the wheat crop to establish, which may have increased moisture- and light-stress for field violet plants.

Domestic and European seedlots, planted into pots in the greenhouse, began to emerge approximately 5 DAP and reached the 2-leaf stage 12 DAP (Figure 4.5). These plants advanced to the rosette stage uniformly at 25 DAP, and continued to produce leaves from axial nodes until 42–43 DAP (Appendix D, Figure D.2.3), at which time stem extension began. Reproductive organs were visible soon after stem extension and developed on domestic plants (49 DAP) an average of three days prior to development on European plants (52 DAP). This was followed by development of seed capsules at 62–64 DAP and release of mature seed at 76–80 DAP. Doohan and Monaco (1992) reported similar plant development under controlled conditions in a greenhouse where field violet was maintained at a 24/18 °C thermoperiod with a Nova Scotia June/July photoperiod. In their experiment, plants developed slowly to the 6-leaf stage (~ one month after germination), at which time the rate of development increased, allowing seed dispersal to occur approximately 70 days after germination.

That field violet was able to reach reproductive maturity faster in field experiments than in the greenhouse suggests that it has a very plastic response to environmental conditions. It may be that when stressed by abiotic and biotic influences, the plant focuses on developing rapidly to seed set to ensure propagation and survival. Under greenhouse conditions, where stress is minimal or nonexistent, the plant develops more leaf tissues, nodes and branches to extend the duration of flowering and maximize seed production. Alternately, the faster rate of development in the field may result from utilization of photosynthetically active radiation, which would have been much greater in the field, especially around the time of the summer solstice. Kakes (1982) reported similar findings in response to environmental conditions, observing that plants experiencing no light-, water- or nutrient-stress became very large and fecund, whereas those competing with winter or spring cereals were generally small, with low reproductive potential.

4.3.5 Competitiveness of field violet with wheat and canola

Large field violet plants (≥ 5-leaf) were present at the time of planting in both years, occurring at a density, averaged across all experiments, of 15 and 45 plants m^{-2} in 2002 and 2003, respectively (Table 4.5). In 2002, the density of large field violet plants tended to increase during early development of crop species, reaching an average of 42 plants m^{-2} in wheat and 86 plants m^{-2} in canola by the crop 3- to 5-leaf stage. The density of large field violet plants remained relatively constant during this phase of crop development in 2003 and did not differ ($P > 0.05$) in any experiment or year between this stage and final counts taken at the soft dough / pod filling stage of development. The density of small (cotyledon to 4-leaf) field violet plants was more variable, peaking at initial and final counts in 2002 and at mid-season (~55 DAP) counts in 2003 (Table 4.5).

Field violet was the most frequent dicotyledonous weed in wheat and canola experiments (~35 DAP) in 2002. The mean density of field violet (≥ 5-leaf) ranged from 42–103 plants m^{-2}, while the mean density of all other species combined ranged from 0–8 plants m^{-2} (data not shown). In corresponding counts (~85 DAP) in 2003, the difference was not as pronounced, with mean field violet density (range: 28–54 plants m^{-2}) exceeding the combined density of all other species by as few as 8 plants m^{-2} in glyphosate-tolerant canola and as many as 37 plants m^{-2} in glufosinate-tolerant canola. Weed species that were most commonly found associated with field violet in weedy plots were lambsquarters (*Chenopodium album* L.), shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], stinkweed (*Thlaspi arvense*), and wild buckwheat (*Polygonum convolvulus* L.).

Growth and fecundity of field violet in wheat tended to be less than in canola in 2002. Field violet was 47% shorter and produced 53% less reproductive units in wheat than canola, averaged across all cultivars (Table 4.6). The number of reproductive units per plant was correlated to plant height ($r = 0.61$, $P < 0.001$, $n = 439$). Field violet abundance was not significantly different between canola cultivars or crop species evaluated in 2003 (Table 4.6). Maximum weed height within crops in 2003 ranged from 47 cm in wheat to 65 cm in glyphosate-tolerant canola (data not shown). Maximum number of reproductive units per plant ranged from 30 to 60, in wheat and canola, respectively. Weed height and the number of reproductive units were correlated, but the correlation was much weaker than in 2002 ($r = 0.28$, $P < 0.001$, $n = 280$). Field violet dry matter comprised 3 to 8% of total dry matter in 2003 (Table 4.6). In accordance with the findings of Kakes (1982), the results of the present study appear to indicate that wheat is more competitive with field violet than canola.

Environmental conditions may have been responsible for fluctuations in measures of field violet abundance. Greater early season rainfall in 2003 relative to 2002 increased weed emergence and resulted in a larger initial density. However, this rainfall also improved the competitive ability of the crop and other weed species relative to field violet, thereby inhibiting growth of smaller plants and leading to mortality of some plants due to shading and nutrient starvation. In 2002, the initial density of large plants was less, but field violet's drought-tolerant nature allowed for the development of smaller plants, ultimately resulting in the establishment of a dense, competitive mat of weeds. Other studies have reported that the density of field violet is greater when competing species are impeded due to drought (Bachthaler *et al.* 1986; Mukula *et al.* 1969).

Losses in crop production due to weed interference varied between cultivars and tended to be more severe in 2002, when moisture was limiting for a large portion of the growing season. Weedy plots of conventional, imidazolinone- and glyphosate-tolerant canola produced 23–31% less seed than weed-free plots in 2002 (Table 4.7). In 2003, the only canola cultivar that yielded significantly less due to weed interference was glufosinate-tolerant canola, which produced 20% less seed in weedy plots relative to weed-free plots. The response of crop biomass accumulation to weed interference was slightly different, although yield and crop biomass were correlated (r =

0.53–0.90, $P < 0.05$) in both years of the experiment. Crop biomass in weedy plots of wheat, imidazolinone- and glufosinate-tolerant canola was 18–30% less, relative to weed-free plots, in 2002. Glufosinate- and glyphosate-tolerant canola had significantly less biomass due to weed interference in 2003.

Regression of measures of field violet abundance on crop biomass and yield indicated that the presence of field violet could explain only a small portion, if any, of crop losses (Table 4.8). In 2002, crop biomass of wheat and glufosinate-tolerant canola was affected by the presence of field violet, which explained 34–35% of variation in crop biomass. At observed average infestation levels in 2002, the regression model suggests that field violet was responsible for 5% of biomass losses for these two crops. Seed yield of wheat in 2002 was affected ($P < 0.05$) by field violet abundance, which led to an estimated 7% yield loss. Regression models for glyphosate- and imidazolinone-tolerant canola indicated that field violet may have affected ($P = 0.06$) seed yield, potentially causing a 4–5% yield reduction. Production losses of conventional canola in 2002 could not be adequately explained by any measure of field violet abundance (Table 8). However, late removal of grass weeds from weedy plots in conventional canola may have been responsible for the observed reduction in seed yield. Weedy plots of conventional canola contained an average of 14 wild oat (*Avena fatua* L.) plants m^{-2} at the time of removal in 2002 (data not shown). Average wild oat density in the other cultivars of canola was 5 plants m^{-2} at the time of removal. Other studies have reported that competition with wild oat can significantly reduce canola yield, especially at the early stages of crop development (Blackshaw *et al.* 1987; Daugovish *et al.* 2003; Martin *et al.* 2001). In 2003, crop biomass losses were linked to field violet abundance for all cultivars except for the conventional canola cultivar Q2, where yield and crop biomass were not different ($P > 0.05$) between weedy and weed free plots (Table 4.8). Estimated biomass reductions due to field violet, at 2003 infestation levels, ranged from 3% in wheat and glyphosate-tolerant canola, to 6–7% in imidazolinone- and glufosinate-tolerant canola. Seed yield was only affected by the presence of this weed in wheat and glufosinate-tolerant canola, where resulting yield loss was estimated to have been 4–5%. The findings of the present study agree with those of Boström *et al.* (2003) who reported that yield loss of spring sown wheat and barley due to interference from a natural weed community was negligibly affected by field violet, even though it was the third most frequent weed (67% of quadrats, n = 1586) and occurred at an average density of 33 plants m^{-2} in weed counts conducted within 7 weeks of crop sowing. Other authors have also reported that field violet is a poor competitor due to its growth habit and shallow depth of recruitment (Gerowitt and Bodendorfer 1998; Semb 1996, 1996b, 1996c).

4.4 Summary

The field violet population found in the Aspen Parkland ecoregion of Alberta is similar to populations from Europe with respect to morphology, phenology and reproductive potential. Leaf width, petal colour, corolla size and seeds per capsule were slightly different between populations. Given the findings of Grundy *et al.* (1995), these differences could be the result of maternal effects, rather than genetic variation. They reported that progeny of field violet plants receiving 160 kg N ha^{-1} and a full rate of the herbicide clopyralid + fluroxypyr + ioxynil (56 + 180 + 250 g ai ha^{-1}), produced 75% less seed capsules 50 DAE than progeny of plants that had not received any herbicide, when both groups were grown under identical conditions in a glasshouse. However, field violet has been present in North America for at least 150 years (Torrey 1843), and thus variation could also be the result of genetic variation caused by different selection pressures on each population. For instance, the smaller, less brilliantly coloured corolla of domestic plants may be the result of selection towards plants with a more autogamous nature and a reduced reliance on insect pollinators that would likely not be present when the first flowers appear in early spring.

The biology of field violet may reduce the efficacy of some management strategies. Due to the periodicity and phenology of weed emergence, a single post-emergence herbicide application in late-June would target only a small proportion of the total number of field violet plants emerged throughout the growing season. In our experiments, only 5 to 31% of total field violet emergence (May to September) occurred from the time of crop seeding to the last week of June. Additionally, cohorts of weed emergence are unpredictable due to annual variation in weather. In a year of adequate precipitation, emergence is constrained by high temperatures and may be limited to periods in the spring to early summer and fall. Alternatively, if moisture is limiting early in the growing season, temperature is no longer restrictive and emergence will occur following rainfall events.

Eliminating seedbank inputs from field violet will likely be difficult due its rapid and variable development. Seed production of winter annuals, if left undisturbed, could presumably begin as early as late-May. Annual plants, emerging early in the growing season could begin to produce seed in July and continue growing vegetatively and reproductively until a killing frost. Under less than optimal conditions, growth of field violet will cease, but the plant may persist in a quiescent state until conditions become conducive for growth and, subsequently, continue to develop.

Field violet may result in more substantial crop losses under drought conditions. Total emergence of field violet was greater in 2002, when rainfall was abnormally low, than in 2003, when rainfall was greater. Despite dry conditions, seed dispersal began from winter and summer annuals in 2002 as early as 4 and 11 weeks after planting, respectively. However, given that crop production losses in both years were seldom attributable to field violet, and never exceeded 10%, it appears that competition from this weed may be agronomically unimportant when other weeds are present.

Our findings have a number of implications for the development of integrated weed management strategies for field violet. Producers could exploit the weakly competitive nature of field violet by using practices that provide crop species an advantage during establishment and development, such as seeding early to make use of early spring moisture, and selecting vigorous crop species and cultivars. In our research, field violet fecundity and plant density (35 DAP) were significantly less in wheat than in canola in 2002; and biomass accumulation of field violet in 2003 tended to be less in glufosinate-tolerant canola, presumably because this cultivar was taller and provided faster canopy closure than other canola cultivars. Increasing crop seeding rate has also been reported to reduce field violet abundance and productivity (Wilson *et al.* 1995). Banding fertilizer may be superior to broadcasting for some crop species, as field violet has a shallow depth of recruitment that could potentially negate utilization of banded fertilizer (Froud-Williams *et al.* 1984). Given our observation that the majority of field violet emergence occurs after June, direct-seeded winter-sown crops may be establishing with greater weed pressure from field than spring-sown crops, which may lead to greater crop production losses. Additionally, our finding suggests that in spring-sown crops, removal of field violet prior to planting, through either a tillage pass or application of a non-selective herbicide, may allow crop establishment to occur without substantial interference from field violet.

Overall, our results suggest that field violet is well adapted to growing conditions and farming practices within Alberta. The weed is very plastic to environmental and anthropogenic variation. When conditions are conducive for growth, plant development slows and the weed will grow tall, produce many branches and a substantial amount of seed. When stressed, the weed advances through growth stages rapidly, but is short and has little reproductive potential. Potential crop production losses due to field violet are minimal in Alberta.

4.5 Tables and figures

Table 4.1 Air temperature, soil temperature, precipitation and growing degree days (5 °C) from May 1 to September 30 at Lamont and Lacombe field experiments in 2002 and 2003.

		Air temperature						Average soil temperature				Total GDD base = 5 °C		Precipitation	
		Mean		Minimum		Maximum		Depth 2.5 cm		Depth 10 cm					
Month	Location	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
		°C										GDD		mm	
May	Lacombe[a]	13	9	1	3	23	15	10	9	10	5	77	159	2	66
	Lamont[a]	14	11	0	4	28	17	11	10	10	10	231	188	5	73
Jun.	Lacombe	17	14	6	8	27	20	17	15	16	7	347	269	7	41
	Lamont	17	14	6	7	29	21	19	15	18	15	374	270	17	88
Jul.	Lacombe	18	18	8	10	27	25	20	20	19	13	387	393	38	20
	Lamont	19	17	9	10	28	23	20	18	20	17	425	363	60	60
Aug.	Lacombe	13	17	5	10	22	25	15	20	14	14	255	392	49	29
	Lamont	14	17	6	9	23	24	15	18	15	18	307	355	54	39
Sep.	Lacombe	8	10	1	4	17	17	11	12	11	7	125	177	21	33
	Lamont	9	10	1	4	19	17	11	12	11	12	154	166	11	61

[a] In 2002, values are the average or sum from May 21– 31 in Lacombe and May 6–31 in Lamont. In 2003, values are the average of sum from May 1–31.

Table 4.2 Selected morphological characteristics of field violet grown from domestic- and European-source seedlots in a greenhouse with a 16 hour photoperiod and an average temperature of 21 °C.

Trait evaluated and corresponding growth stage (BBCH)			Observed experimental values								Literature Value
			Domestic seedlot				European seedlot				
Trait	Stage		N	Min.	Max.	Mean[ζ]	N	Min.	Max.	Mean[ζ]	
Cotyledon width	13	mm	95	4	8	6 ± 0.1	125	5	7	6 ± 0.1	3 – 4[α]
Cotyledon length	13		95	5	9	7 ± 0.2	125	6	9	7 ± 0.1	3 – 5[α]
Lower blade width	22		18	15	22	18 ± 1	18	16	24	20 ± 1	10 – 15[α]
Lower blade length	22		18	16	30	25 ± 2	18	22	29	26 ± 1	10 – 15[α]
Petiole length	22		18	20	35	29 ± 2	18	17	37	27 ± 2	10 – 20[α]
Lower blade width	69		91	15	31	23 ± 1	90	17	39	27 ± 1	10 – 15[α]
Lower blade length	69		91	19	52	36 ± 2	90	21	54	37 ± 2	10 – 15[α]
Upper blade width	69		91	13	29	20 ± 1	87	11	29	21 ± 1	10 – 17.5[α]
Upper blade length	69		91	23	46	36 ± 1	87	25	51	37 ± 1	20 – 80[α]
Erect stem length	69		18	196	304	239 ± 15	18	115	325	225 ± 26	300 – 795[β,γ]
Prostrate stem length	92		18	490	870	615 ± 44	18	440	1350	749 ± 108	300 – 795[γ,δ]
Open flower width	69		91	11	17	15 ± 0.3	87	11	22	16 ± 0.5	10[β]
Open flower length	69		91	13	21	18 ± 0.3	87	13	28	20 ± 0.7	10 – 15[β]
Fresh weight	92	g	18	145	204	172 ± 9	18	124	243	174 ± 15	–
Dry weight	92		18	26	52	33 ± 3	18	27	46	34 ± 3	–
Water content	92	%	18	67	85	81 ± 2	18	75	84	80 ± 1	–

[ζ] Mean ± 95% confidence interval of the mean.

[α] Doohan and Monaco 1992; [β] Gleason and Cronquist 1991; [γ] Gerowitt and Bodendorfer 1998.

Abbreviations: Min., minimum; max., maximum.

Table 4.3 Seed production and seed weight of field violet grown from domestic- and European-source seedlots for 25 weeks in a greenhouse with a 16 hour photoperiod and an average temperature of 21 °C.

		Observed experimental values								
		Domestic seedlot				European seedlot				Literature Value
Attribute		N	Min.	Max.	Mean[ζ]	N	Min.	Max.	Mean[ζ]	
Capsule prolificity (seeds capsule $^{-1}$)		180	12	81	52 ± 2	175	6	76	38 ± 2	45 – 80[α,β]
Capsule production (capsules plant^{-1})	0 – 15 WAP	18	126	267	182 ± 16	18	23	303	134 ± 40	–
	16 – 25 WAP	18	432	721	582 ± 42	18	570	1001	740 ± 64	–
	TOTAL	18	589	950	764 ± 54	18	701	1238	874 ± 85	–
Total seed production[ε] (× 10^3 plant $^{-1}$)		18	29.7	52.2	39.5 ± 2.9	18	10.1	66.4	33.7 ± 7.8	20 – 46[γ]
1000-seed weight (g)		15	0.69	0.84	0.77 ± 0.03	15	0.69	0.92	0.79 ± 0.04	–

[ζ] Mean ± 95% confidence interval of the mean.

[α] Bachthaler *et al*. 1986; [β] Korsmo 1930; [γ] Doohan and Monaco 1992.

[ε] Calculated as: capsule prolificity × total capsules production

Abbreviations: Min., minimum; max., maximum; WAP, weeks after planting.

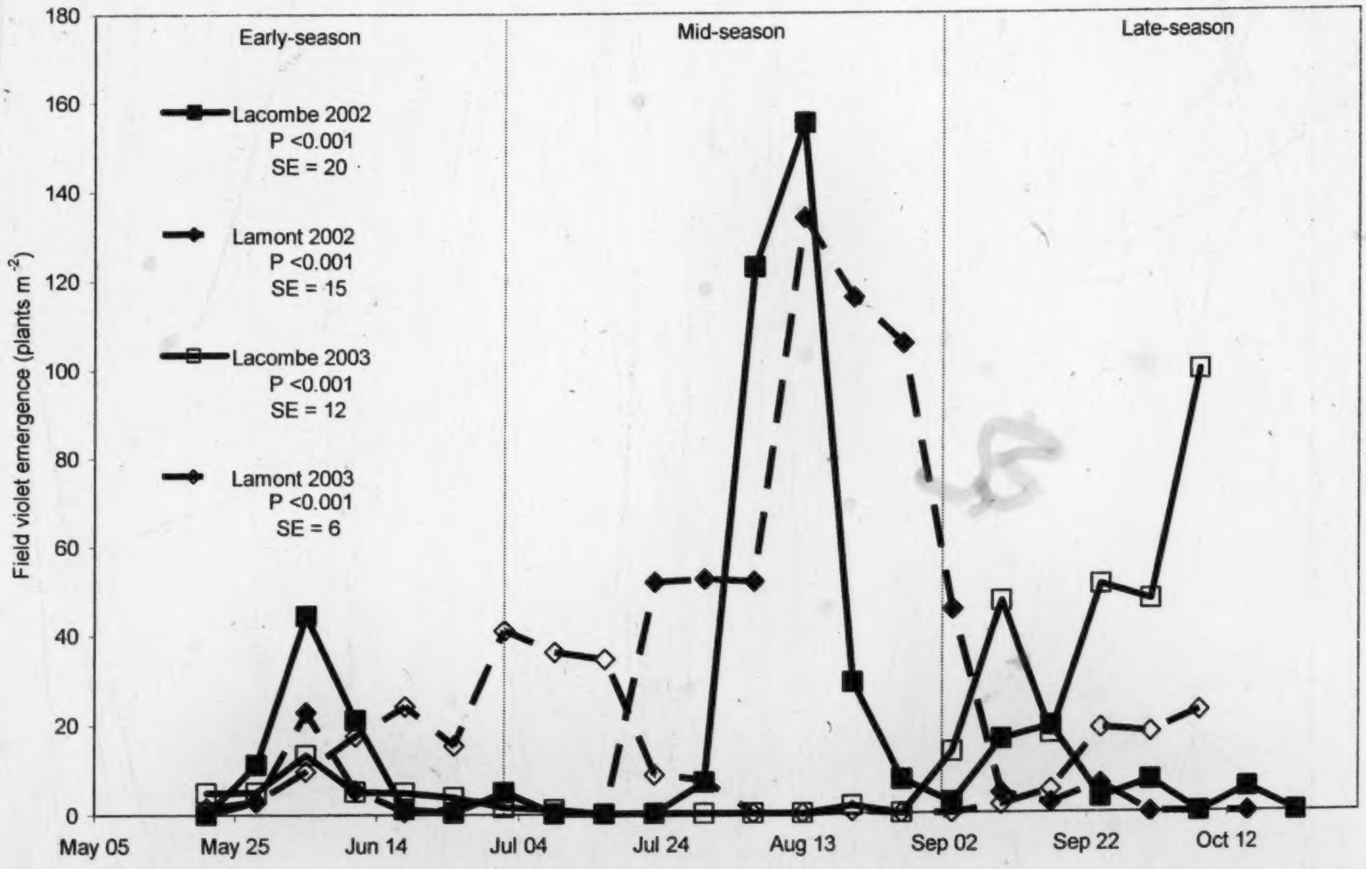

Figure 4.1 Field violet emergence periodicity at Lamont and Lacombe field sites in 2002 and 2003. P-value is the probability of no difference in emergence between weeks. Standard error (SE) is of the difference between least square means.

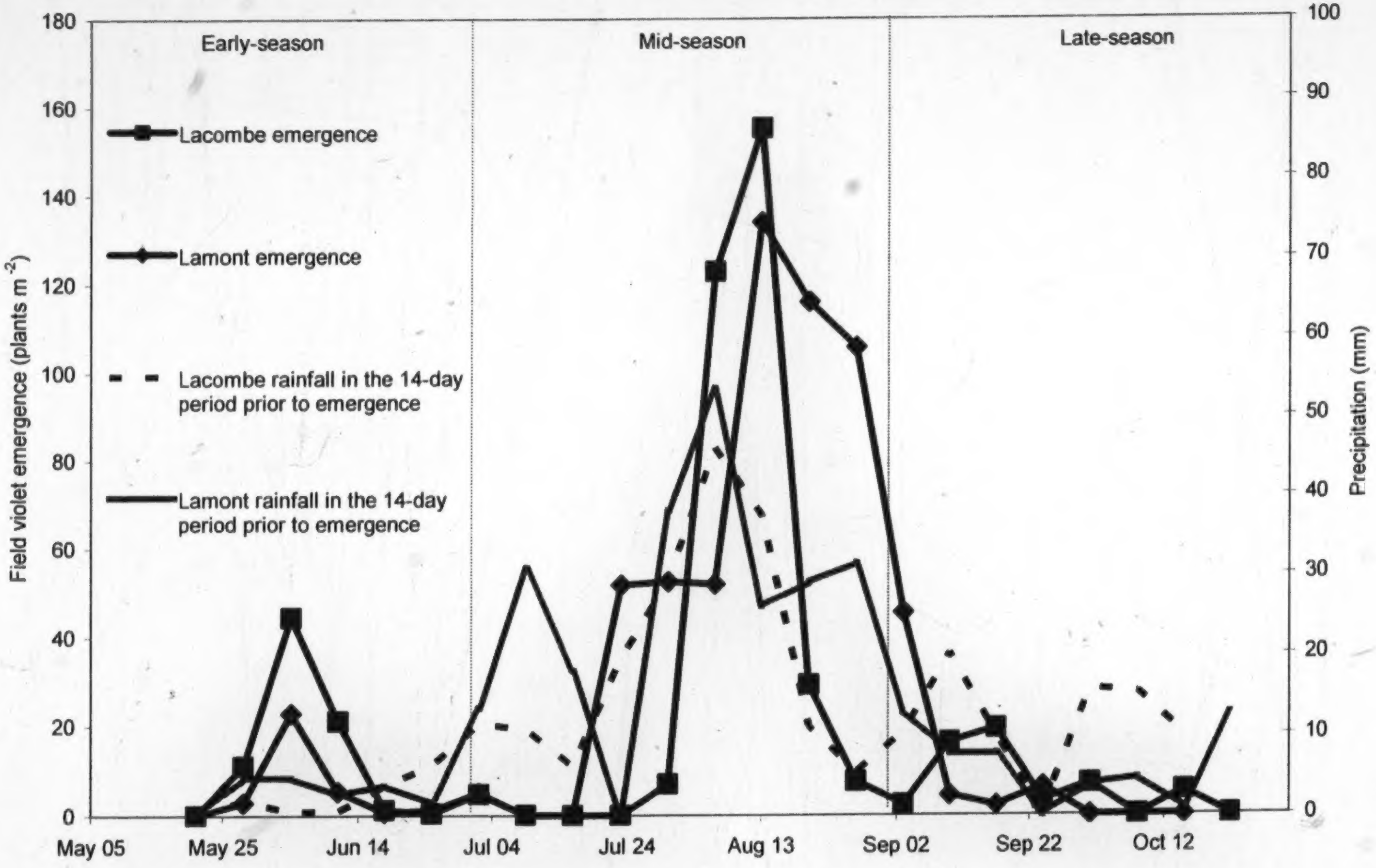

Figure 4.2 Field violet emergence periodicity and rainfall at Lamont and Lacombe field sites in 2002.

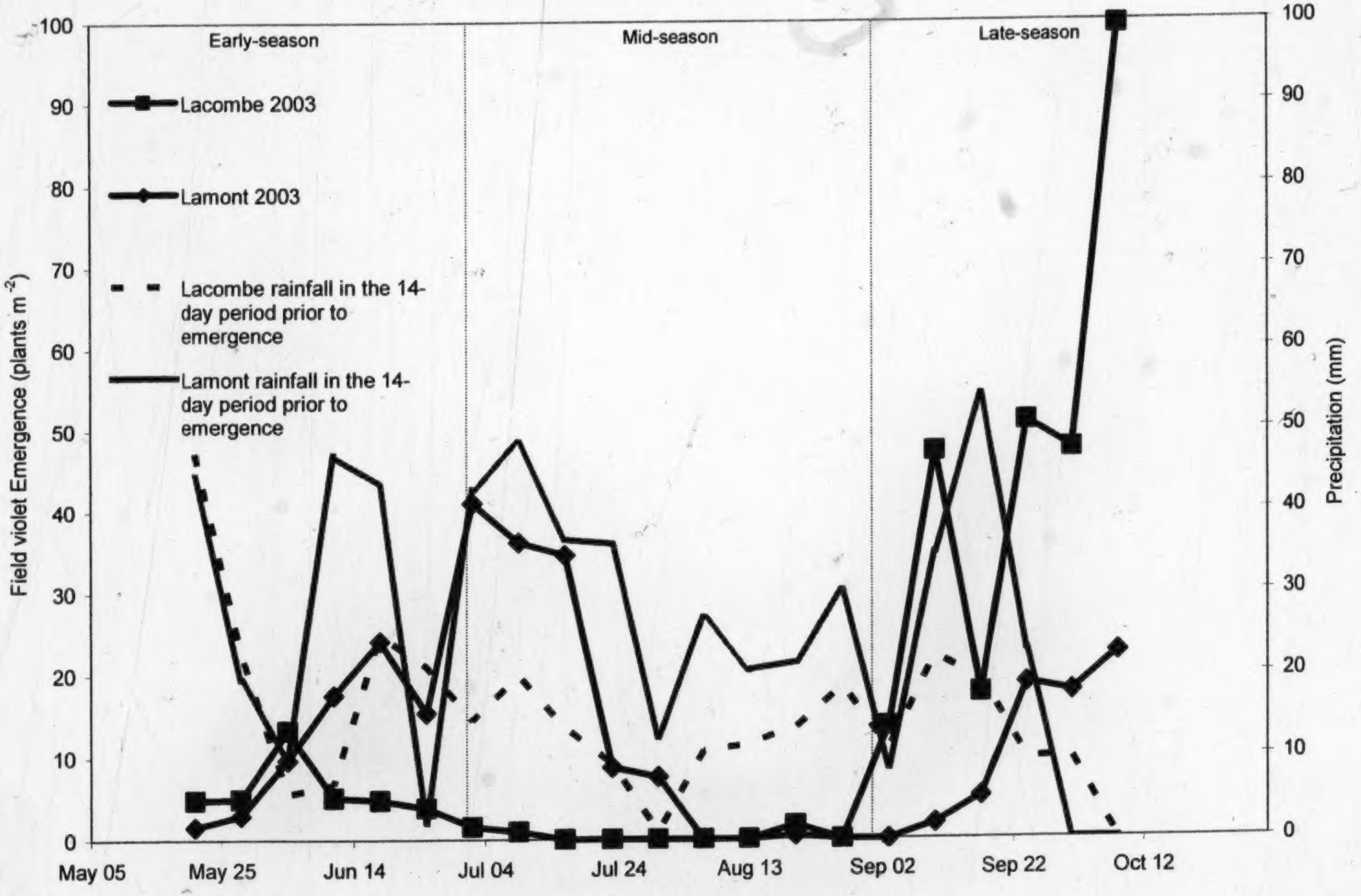

Figure 4.3 Field violet emergence periodicity and rainfall at Lamont and Lacombe field sites in 2003.

Table 4.4 Relationship between meterological variables (7–14 DBE) and emergence of field violet within spring wheat in field experiments conducted at Lamont and Lacombe in 2002 and 2003.

Meteorological variables	Early-season[α]		Mid-season[α]		Late-season[α]	
	2002	2003	2002	2003	2002	2003
	Pearson correlation coefficient (r)[β]					
Diurnal temp. fluctuation	–	–	-0.6	-0.7	–	–
Maximum air temp.	-0.5	–	-0.5	-0.6	**0.4**	–
Minimum air temp.	–	–	–	–	**0.5**	–
Average air temp.	–	–	-0.5	-0.5	**0.5**	–
Average soil temp. at 2.5	–	–	-0.5	-0.6	**0.4**	–
Average soil temp. at 10	–	**0.5**	-0.4	–	**0.5**	-0.5
Growing degree days	–	–	-0.5	-0.5	**0.5**	–
Rain	–	–	**0.4**	**0.6**	–	–

[α] Early, mid- and late-seaon correspond to calendar dates of May 20 – June 30, July 1 – August 30 and September 30 – experiment end, respectively.

[β] Only correlations significant after adjusting the P-value using the bonferroni technique ($P < 0.0005$) are presented. Correlation coefficents less than 0.4 were not considered to be biologically relevant and thus are not presented.

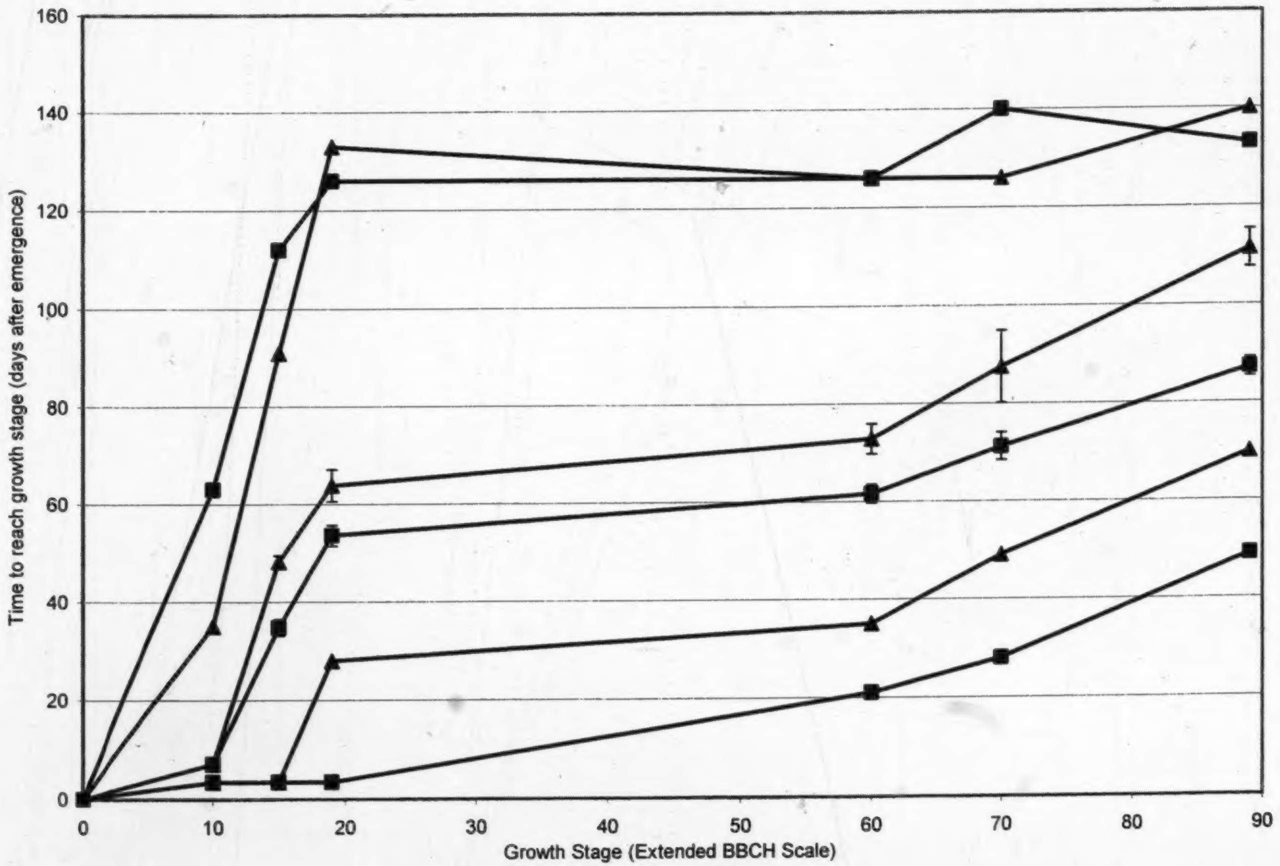

Figure 4.4 Growth staging (BBCH) of field violet in spring wheat in field experiments conducted at Lamont and Lacombe in 2002 and 2003. Data presented was combined over both locations. Symbols: ▲, observed development in 2002; ■, observed development in 2003. Upper, middle and lower lines represent observed maximum, mean and minimum responses, respectively. Bars extending from symbols are one standard error of the mean (n = 14–242). Corresponding descriptive stages for BBCH scale are: 11 = one-leaf, 15 = five-leaf, 19 = full rosette, 51 = stem extension, 61 = reproductive organs visible to flowering, 71 = seed capsules present, and 89 = dispersal of mature seed.

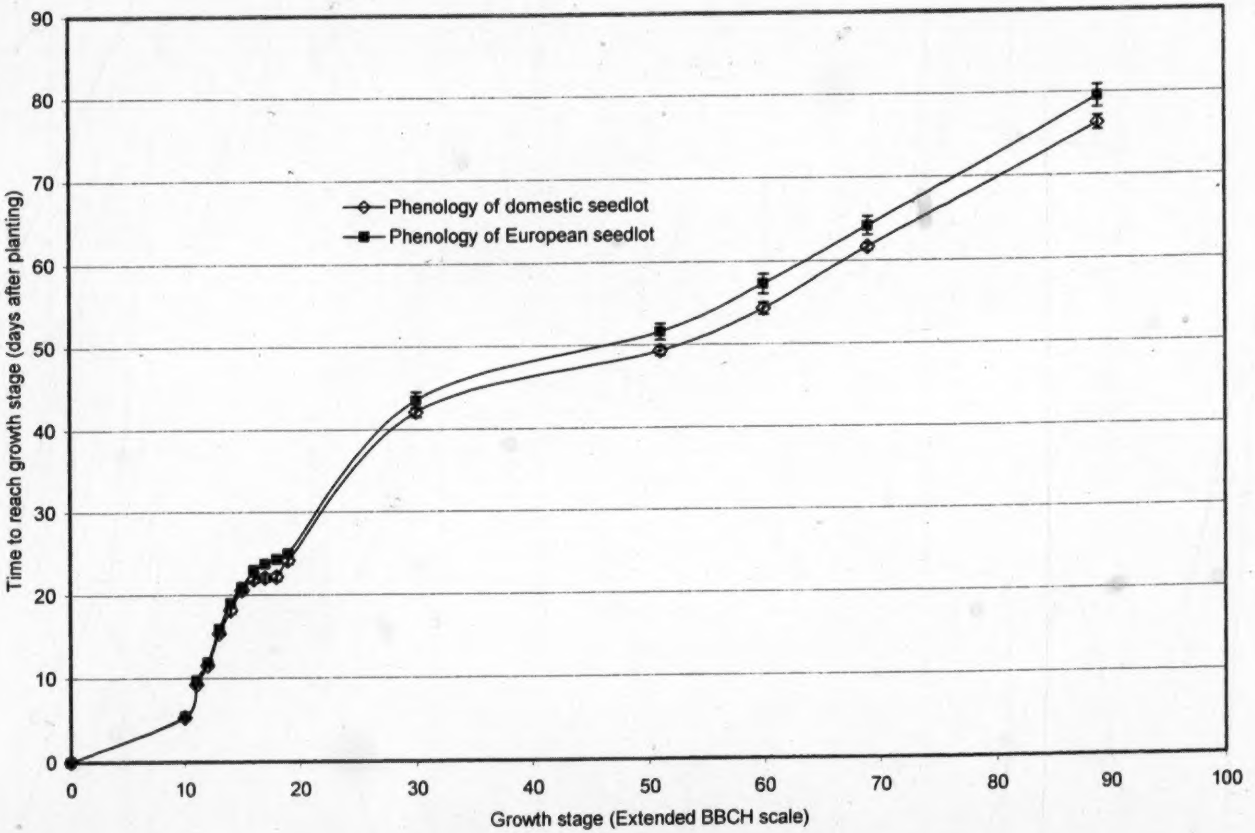

Figure 4.5 Growth staging (BBCH extended) of field violet grown in a greenhouse with a 16 hour photoperiod and an average temperature of 21 °C from seed harvested in the Aspen Parkland ecoregion of Alberta (domestic) and from seed obtained from Herbiseed® (European) that was originally harvested in the county of Berkshire, UK. Symbols (squares and tetragons) and bars represent means ± one standard error of the mean (n = 18). Corresponding descriptive stages for BBCH scale are: 11 = one-leaf, 15 = five-leaf, 19 = full rosette, 51 = stem extension, 61 = reproductive organs visible to flowering, 71 = seed capsules present, and 89 = dispersal of mature seed.

Table 4.5 Density of small (cotyledon to 4-leaf) and large (5+ leaf) field violet plants in canola and wheat crops in field experiments conducted at Lamont and Lacombe in 2002 and 2003.

	2002								2003							
	Density of small weeds				Density of large weeds				Density of small weeds				Density of large weeds			
	Timing of count (DAP)				Timing of count (DAP)				Timing of count (DAP)				Timing of count (DAP)			
Crop	0	35	55	85	0	35	55	85	0	35	55	85	0	35	55	85
	No. m^{-2}								No. m^{-2}							
Wheat	358	17	1	326	19	42	24	35	51	56	81	7	45	46	83	43
Canola	392	38	10	508	13	86	53	70	71	108	123	3	46	29	88	44
SE[α]	125	10	3	105	11	16	9	15	39	43	53	3	25	10	12	10
Contrasts	F-test[β]								F-test[β]							
Wheat vs. all canola cultivars	ns	0.05	<0.01	ns	ns	0.01	0.06	0.08	ns	ns	ns	ns	ns	ns	ns	ns
Imidazolinone-tolerant (45A77) vs. other canola cultivars	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.01	ns
Glyphosate-tolerant (DKL34-55) vs. other canola cultivars	ns	ns	ns	ns	ns	ns	ns	0.05	ns	0.05	0.09	ns	ns	ns	<0.01	0.06
Glufosinate-tolerant (Invigor 2663) vs. other canola cultivars	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.09	ns	ns	0.02	ns
Conventional (Q2) vs. other canola cultivars	ns	0.06	ns	ns	ns	ns	ns	ns	ns	0.06	0.08	ns	ns	ns	<0.01	ns

[α] Standard error of the estimated difference between least square means.

[β] P-value for contrast F-tests with a single degree of freedom. Contrasts considered not significant (ns) when P ≥ 0.10.

Table 4.6 Effect of crop and cultivar selection on field violet growth and abundance in field experiments conducted at Lamont and Lacombe in 2002 and 2003.

		2002				2003			
Crop	Cultivar and management system	Biomass (dry)	Relative biomass (dry)	Height[α]	Reproductive potential[α]	Biomass (dry)	Relative biomass (dry)	Height[α]	Reproductive potential[α]
		– g m^{-2} –	— % —	– cm –	– RU plant^{-1} –	– g m^{-2} –	— % —	– cm –	– RU plant^{-1} –
Wheat	AC Barrie Conventional	9	5	6	3	23	4	18	13
Canola	45A77 Imidazolinone-tolerant	19	9	9	5	33	7	28	13
	DKL34-55 Glyphosate-tolerant	28	12	10	6	14	3	25	15
	Invigor 2663 Glufosinate-tolerant	12	6	9	5	20	5	24	16
	Q2 Conventional	23	10	9	5	41	8	23	13
	SE[β]	5	2	1	1	10	2	6	3
Contrasts		F-test[γ]				F-test[γ]			
Wheat vs. all canola cultivars		0.06	0.09	0.01	0.03	ns	ns	ns	ns
45A77 vs. other canola cultivars		ns	ns	ns	ns	ns	ns	ns	ns
DKL34-55 vs. other canola cultivars		ns	ns	ns	ns	ns	ns	ns	ns
Invigor 2663 vs. other canola cultivars		ns	ns	ns	ns	ns	ns	ns	ns
Q2 vs. other canola cultivars		ns	ns	ns	ns	ns	ns	ns	ns

[α] Measurements were taken 9 weeks after planting in 2002 and 13 weeks after planting in 2003

[β] Standard error of the estimated difference between least square means

[γ] P-value for contrast F-tests with a single degree of freedom. Contrasts considered not significant (ns) when $P \geq 0.10$.

Abbreviations: RU, reproductive units.

Table 4.7 Seed yield and above-ground biomass of wheat and canola grown without weeds, or with a natural weed flora including field violet in experiments conducted at Lamont and Lacombe in 2002 and 2003.

		2002								2003							
		Crop biomass (dry) 10 WAP				Seed yield				Crop biomass (dry) 10 WAP				Seed yield			
Crop	Cultivar and management system	Weedy plots	Weed-free plots	SE[α]	F-test[β]	Weedy plots	Weed-free plots	SE[α]	F-test[β]	Weedy plots	Weed-free plots	SE[α]	F-test[β]	Weedy plots	Weed-free plots	SE[α]	F-test[β]
		—— g m^{-2} ——				— kg ha^{-1} —				—— g m^{-2} ——				— kg ha^{-1} —			
Wheat	AC Barrie Conventional	204	248	19	0.05	706	788	115	ns	548	593	39	ns	2998	3443	415	ns
Canola	45A77 Imidazolinone-tolerant	187	234	14	0.02	745	1083	119	0.02	475	578	50	0.07	2024	2323	218	ns
	DKL34-55 Glyphosate-tolerant	230	280	24	ns	1060	1375	121	0.05	545	622	30	0.04	2357	2577	200	ns
	Invigor 2663 Glufosinate-tolerant	190	271	8	<0.01	1133	1381	196	ns	592	705	38	0.02	2311	2879	171	0.01
	Q2 Conventional	189	221	38	ns	897	1293	124	<0.01	509	542	22	ns	1832	2084	180	ns

[α] Standard error of the estimated difference between least square means.

[β] P - value for F-tests of the assumption that least square means of weedy and weed-free plots are identical. Means considered not significantly different when P ≥ 0.10.

Abbreviations: WAP, weeks after planting.

Table 4.8 Regression of canola and wheat seed yield and biomass (10 WAP) on measures of field violet abundance within field experiments conducted at Lamont and Lacombe in 2002 and 2003.

			2002							2003						
Crop	Cultivar and management system	Measure of crop production	Measure of field violet abundance[α]	Average infestation level (x)	Parameter estimates[β] (± SE) Int (a)	Parameter estimates[β] (± SE) Slope (b)	Model F-test[γ]	R^2[δ]	% losses due to field violet[ε]	Measure of field violet abundance[α]	Average infestation level (x)	Parameter estimates[β] (± SE) Int (a)	Parameter estimates[β] (± SE) Slope (b)	Model F-test[γ]	R^2[δ]	% losses due to field violet[ε]
Wheat	AC Barrie	Yield	Biomass	9 g m^{-2}	861 (95)	-26 (12)	0.05	0.25	7	% biomass	4%	3460 (186)	-113 (50)	0.04	0.26	4
	Conventional	Biomass	% biomass	5%	243 (12)	-7 (3)	0.02	0.34	5	% biomass	4%	608 (25)	-18 (7)	0.04	0.27	3
Canola	45A77	Yield	No. 85 DAP	69 m^{-2}	1007 (84)	-3 (1)	0.06	0.25	5	No. 55 DAP	61 m^{-2}	2277 (229)	-5 (5)	ns	0.05	–
	Imidazolinone-tolerant	Biomass	No. 85 DAP	69 m^{-2}	222 (20)	0 (0)	ns	0.08	–	% biomass	7%	567 (27)	-12 (4)	0.01	0.40	6
	DKL34-55	Yield	% biomass	12%	1343 (103)	-20 (10)	0.06	0.24	4	No. 55 DAP	61 m^{-2}	2558 (195)	-3 (4)	ns	0.03	–
	Glyphosate-tolerant	Biomass	% biomass	12%	272 (23)	-3 (2)	ns	0.11	–	No. 85 DAP	29 m^{-2}	620 (24)	-2 (1)	0.03	0.29	3
	Invigor 2663	Yield	No. 85 DAP	47 m^{-2}	1298 (114)	-2 (3)	ns	0.06	–	% biomass	5%	2695 (326)	-94 (48)	0.03	0.33	5
	Glufosinate-tolerant	Biomass	% biomass	6%	249 (16)	-6 (3)	0.02	0.35	5	% biomass	5%	697 (50)	-26 (10)	0.01	0.41	7
	Q2	Yield	No. 35 DAP	75 m^{-2}	1153 (121)	-1 (2)	ns	0.03	–	No. 85 DAP	48 m^{-2}	1561 (319)	12 (7)	ns	0.22	–
	Conventional	Biomass	Biomass	23 g m^{-2}	200 (19)	0 (1)	ns	0.02	–	No. 85 DAP	48 m^{-2}	452 (50)	2 (1)	ns	0.18	–

[α] Measures selected from a stepwise regression based on their ability to explain the largest amount of variation in crop production.

[β] Parameter estimates for linear function $y_1 = a + bx$, where y_1 is crop production with weeds present (seed yield or shoot biomass), a is crop production with weeds absent, b is the slope coefficient and x is the infestation level of field violet.

[γ] P - value for regression model F-test. Models considered not significant when $P \geq 0.10$.

[δ] Proportion of variation in crop production attributable to interference from field violet.

[ε] Caclulated as $y_2 = 100 \times \{1 - [(a + bx \times R^2) / a]\}$, where a, b and x are the same as above, y_2 is the percentage loss due to field violet and R^2 is the proportion of variation in crop production attributable to field violet.

Abbreviations: Yield, seed yield; % biomass, relative weed biomass; No., plant density; Int, intercept; SE, standard error of parameter estimate; DAP, days after planting.

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Chapter 5
Synthesis

5.1 Background

Field violet has been studied extensively in Europe due to its persistence within disturbed environments and its abundance in agricultural fields (Bachthaler *et al.* 1986; Hyvonen *et al.* 2003; Schroeder *et al.* 1993). Studies indicate that the weed has a number of biological attributes that make it a concern within agricultural systems. Specifically, it exhibits variable patterns of dormancy and has been classified as a facultative winter annual due to its ability to germinate throughout the growing season (Baskin and Baskin 1995, 2001); viable seed can persist within the seedbank for an extended period of time, possibly hundreds of years (Odum 1965); it is very plastic in response to environmental variation, adopting a large, spreading, growth habit under low-stress conditions and a short, upright, growth habit under high-stress conditions (Kakes 1982); it flowers indeterminately and is fecund, with single plants producing as many as 270 to 2500 seeds annually, in-crop (Bachthaler *et al.* 1986; Gerowitt and Bodendorfer 1998); it is cold-, shade- and drought-tolerant, capable of colonizing acid and alkaline soils, and reportedly has a preference for tilled fields (Bachthaler *et al.* 1986; Doohan and Monaco 1992); it causes quality and yield reductions in cereal and oilseed crops (Bachthaler *et al.* 1986; Wilson *et al.* 1995); it is tolerant of many crop-selective herbicides (Doohan and Monaco 1992; Richardson and West 1985). In Canada, it is present in all 10 provinces and has been studied in horticultural crops in eastern Canada (Doohan and Monaco 1992; Doohan *et al.* 1993). To date, there has been no research conducted on field violet in western Canada.

The underlying purpose of this thesis was to characterize natural field violet populations within conservation tillage farm systems in Alberta and identify options for management. Chapter 1 provided the context for the present research by describing the habitat, morphology and geography of field violet, and outlined the research already conducted on populations in other regions. Chapter 2 examined the management of natural field violet populations in Alberta in spring wheat under a reduced-tillage cropping system, while Chapter 3 similarly investigated management in conventional- and herbicide-tolerant canola cultivars under a reduced-tillage cropping system. Chapter 4 examined biological attributes that could be exploited to develop effective integrated weed management strategies in Alberta.

5.2 Specific objectives of thesis research conducted on field violet in Alberta

Herbicide control of field violet in wheat

1. Evaluate field violet control obtained with herbicides registered for post-crop emergence (POST) application on hard red spring wheat in Alberta.
2. Determine if a pre-crop emergence (PRE) application of a non-selective herbicide without residual activity (glyphosate), or a non-selective herbicide with residual activity (glyphosate + florasulam), could maintain season-long control of field violet in spring wheat.

Herbicide control of field violet in canola

1. Evaluate the efficacy of POST herbicides against field violet in conventional, imidazolinone-tolerant, glufosinate-tolerant and glyphosate-tolerant canola cultivars and management systems.
2. Identify the most effective time and rate of glyphosate application for control of field violet in glyphosate-tolerant canola.
3. Determine the most agronomically acceptable herbicide treatment(s) from those evaluated.

Biology of field violet in Alberta

1. Identify differences in the biology (morphology, development, productivity) of populations of field violet from Europe and Alberta in a controlled environment.
2. Characterize emergence periodicity and phenology, plant development and lifecycle of field violet in spring wheat under a reduced-tillage production system.
3. Quantify field violet's contribution to production losses of spring wheat and canola caused by a natural weed flora.
4. Investigate the effects of crop and cultivar selection on field violet growth and fecundity.

5.3 Summation of results

5.3.1 Herbicide control of field violet in wheat

- Most herbicides evaluated were less effective in a year of abnormally low precipitation than in a year when precipitation was greater. This difference was most pronounced for the Group 2 (Mallory-Smith and Retzinger, 2003) herbicides, which inhibit the formation of branched-chain amino acids at the cellular level.
- Under drought conditions, only POST fluroxypyr + 2,4-D LV ester 600 provided control of field violet, reducing weed biomass 5 weeks after treatment (WAT) and plant density 8 WAT by 59 and 91%, respectively, from untreated controls. Efficacy of this herbicide was consistent in a non-drought year, conferring 69, 83 and 86% reductions in weed biomass 5 WAT, plant density 8 WAT and reproductive potential, respectively, relative to the untreated control.
- Applied POST, MCPA + mecoprop + dicamba suppressed weed growth in both drought and non-drought years, while metribuzin suppressed weed growth only in a non-drought year.
- Group 2 herbicides, metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl controlled field violet when applied POST in a non-drought year. Plant density following their application was 82–92% less than initial densities and 81–89% less than untreated control densities, 8 WAT.
- Field violet was tolerant of POST applications of florasulam + MCPA ester (Group 2 + 4), bentazon (Group 6) and linuron (Group 7).
- The estimated herbicide dose required to reduce field violet dry weight by 85% (ED_{85}) in the greenhouse was less than the recommended rate used in field experiments for metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl, fluroxypyr + 2, 4-D LV ester 600 and metribuzin.
- Estimated ED_{85} values for florasulam + MCPA ester and MCPA + mecoprop + dicamba were slightly greater than the rates used in field experiments, whereas estimated values for linuron and bentazon were much greater than rates evaluated in the field.
- Application of PRE glyphosate provided acceptable season long control of field violet in 2003 and weeds receiving this treatment accumulated little above-ground biomass (< 0.5

g m^{-2}) and had low reproductive potential (< 3 reproductive units plant^{-1}). The addition of florasulam, a Group 2 herbicide with residual activity, to glyphosate did not significantly improve control over that obtained from glyphosate alone.

5.3.2 Herbicide control of field violet in canola

- Neither of the POST herbicides evaluated in conventional canola (ethametsulfuron-methyl + quizalofop-p-ethyl and clopyralid) had any effect on field violet in the field at recommended rates, or in the greenhouse at rates up to 300% of recommended.
- Thifensulfuron methyl + quizalofop-p-ethyl (15+ 48 g ai ha^{-1}), a Group 2 herbicide, provided acceptable control of field violet in 2003 when applied POST to imidazolinone-tolerant canola, and to plants in the greenhouse. Plants surviving this treatment in field experiments generally had a winter annual life cycle and were quite large (> 10-leaf) at the time of herbicide application.
- Field violet growth in 2002 was not altered by thifensulfuron methyl + quizalofop-p-ethyl when applied POST to quiescent, drought-stressed plants, but was suppressed when it was applied to plants that were actively growing at the time of application and became inactive due to drought shortly thereafter.
- Imazamox + imazethapyr had no activity on field violet in field experiments and caused only a 22% reduction in weed dry weight when applied in the greenhouse at 300% of the recommended rate employed in the field.
- Efficacy of POST glufosinate ammonium (500 g ai ha^{-1}) in glufosinate-tolerant canola was not consistent, having no affect on field violet in 2002 when applied to quiescent, drought-stressed plants, but reducing weed density 8 WAT by 81% relative to untreated controls in 2003 when applied to actively growing plants. Results suggest that this herbicide is only effective when the crop canopy is able to close rapidly following herbicide application, shading surviving weeds and ultimately leading to their mortality.
- In the greenhouse, glufosinate ammonium caused substantial chlorosis and stunting at rates as low as 100 g ai ha^{-1}, however, plants were able to recover from axial buds and compensated for mortality with vigorous growth of remaining plants, resulting in an extrapolated ED_{85} of 619 g ai ha^{-1}.
- Control of field violet following a POST application of glyphosate (445 g ae ha^{-1}) in glyphosate-tolerant canola was moderate to high. Weed biomass 5 WAT was reduced by

this application, relative to untreated controls, by 76 and 85% in 2002 and 2003, respectively.

- Glyphosate was more active in field experiments when applied POST to actively growing plants in 2003 (estimated $ED_{85} = 290$ g ae ha^{-1}) than to quiescent, drought-stressed plants in 2002 (estimated $ED_{85} = 565$ g ae ha^{-1}). In the greenhouse, the estimated ED_{85} was 360 g ae ha^{-1}.
- Efficacy of PRE glyphosate, as measured quantitatively and by visual estimates of weed control, was equivalent to control with POST glyphosate at a rate of 1334 g ae ha^{-1}. Post-harvest (FALL) application effectively managed plants present in the fall, but provided less overall control, in-crop, than glyphosate applied PRE. There were no additive effects of FALL + PRE applications, as this treatment provided no greater control than a PRE application alone.
- In competition with a natural weed community containing field violet, the crop production of glufosinate-tolerant, imidazolinone-tolerant and glyphosate-tolerant canola cultivars tended to be greatest in plots receiving POST applications of glufosinate ammonium, imazamox + imazethapyr and glyphosate (222–890 g ae ha^{-1}), respectively. Glyphosate-tolerant canola in plots receiving PRE and FALL + PRE glyphosate applications yielded equivalent to, or better than, the highest yielding plots receiving a POST application.

5.3.3 Biology of field violet in Alberta

- Cotyledons, lower leaves, petioles and the corolla of domestic field violet plants grown in the greenhouse were 20 to 140% larger than those of previously-described plants in the northeastern United States and eastern Canada.
- Estimated seed production of field violet during a 180 day period in the greenhouse ranged from 30,000 to 52,000 seeds per plant, with a mean of 40,000. Plants produced 24% of this total in the first 15 weeks after planting and the remainder in the final 11 weeks of growth.
- Thousand seed weight of field violet averaged 0.77 g.
- The population found in the Aspen Parkland ecoregion of Alberta is similar to populations from Europe with respect to morphology, phenology and reproductive

potential; however the former has a smaller corolla and less brilliantly colored petals, which may reflect a shift towards autogamy.

- The natural field violet population present in field experiments had three growth habits: annual, winter annual and short-lived perennial. The perennial lifecycle has not been previously reported in populations outside of Canada.
- Field violet emerged intermittently throughout the growing season. The period of maximum emergence was variable, but conserved across all field experiments were two periods of peak emergence, in early June and September.
- Total field violet emergence during the growing season was greater in 2002 ($\bar{x} = 531$ plants m^{-2}), when precipitation was abnormally low, than in 2003 ($\bar{x} = 291$ plants m^{-2}), when precipitation was greater.
- Early- (May 20 to June 30) and late-season (September 1 to experiment end) emergence was not consistently linked to any weather parameters.
- Precipitation and low temperatures were important prerequisites for mid-season emergence. Field violet did not emerge in 2003 when the maximum and minimum temperatures, averaged over the period 14 days before emergence, were greater than 24 and 10 °C, respectively.
- When precipitation was limiting during the early-season in 2002, temperature was less restrictive to emergence and field violet emerged abundantly following mid-summer rainfall events.
- Following a mild winter, winter annual plants were observed at the flowering stage by late-April to early-May.
- When conditions were conducive for growth, summer-annual field violet plants in spring wheat developed rapidly, flowering as soon as 3 weeks after emergence (WAE), producing seed capsules 4 WAE, and dispersing mature seed 7 WAE.
- Winter annuals began to flower and disperse seed as early as 3 and 8 weeks after crop sowing, respectively.
- Under adverse environmental conditions, field violet plants entered into a dormant state for extended periods of time. Rosettes persisted in this state for as long as 19 weeks.

- In the greenhouse, seeds planted into pots emerged uniformly 5 days after planting (DAP). These plants advanced to the rosette stage 25 DAP, and continued to produce leaves from axial nodes until 42 DAP, at which time stem extension began. Reproductive organs were visible soon after stem extension (49 DAP) and this was followed by development of seed capsules at 62 DAP and release of mature seed at 76 DAP.
- Field violet was the most frequent dicotyledonous weed in all canola and wheat experiments.
- Yield loss in wheat due to interference from field violet ranged from 4 to 7%. Losses in canola ranged from 0–6% of seed yield and 0–7% of crop biomass.
- Field violet was 47% shorter and produced 53% less reproductive units in wheat than canola, averaged across all cultivars, in 2002.
- Maximum weed height within crops in 2003 ranged from 47 cm in wheat to 65 cm in glyphosate-tolerant canola. The maximum number of reproductive units per plant ranged from 30 in wheat, to 60 in glyphosate-tolerant canola.

5.4 Contributions to knowledge

Research presented in this thesis was novel as there has been no previous work conducted on field violet in western Canada. Experiments conducted in spring wheat, the most widely cultivated crop in Alberta in 2001 (Statistics Canada 2002), demonstrated that a number of commonly-used, registered herbicides provided effective control of field violet. Efficacy of some herbicides, such as fluroxypyr + 2-4,D LV ester 600, was found to be greater and more consistent than has previously been reported. Herbicide classifications by site of action (Mallory-Smith and Retzinger 2003) could not be used to predict control of field violet. For instance, while the Group 4 herbicide fluroxypyr + 2,4,D LV ester 600 conferred control of field violet, another Group 4 herbicide, MCPA + mecoprop + dicamba, only suppressed weed growth. A similar exception was florasulam + MCPA ester (Group 2 + 4), which had no activity in field experiments, while other Group 2 herbicides had good activity. This finding is important because it suggests that other herbicides will have to be evaluated on field violet in replicated experiments, and not simply recommended based on their chemistry. That herbicides with different modes of action were able to control field violet is important because it suggests that producers can rotate between herbicide Groups to delay / prevent selection of herbicide resistance. Control observed in the present study following application of PRE glyphosate and glyphosate + florasulam may allow producers who use a PRE application to select in-crop herbicides strictly based on other weeds present. Rainfall, soil moisture and the rate of field violet growth at the time of herbicide application were found to be important factors controlling herbicide activity, especially for the Group 2 herbicides. Weed size and application volume used were also important, as herbicides applied with a larger volume in the greenhouse to smaller weeds had greater efficacy than those applied in the field. These findings indicate that producers may have to monitor fields and alter application timing of herbicides to target field violet plants when they are young, actively growing and environmental conditions are conducive for growth. ED_{50} and ED_{85} values derived from greenhouse experiments improve of our understanding of field violet's susceptibility to a number of herbicides, provide a basis for herbicide selection for experimental and practical applications in other jurisdictions, and potentially indicate effective management options for other crops that evaluated herbicides are registered for.

Experimental results in canola, the most common oilseed cultivated in Alberta (Statistics Canada 2002), indicated that control of field violet with POST herbicides may be limited or negligible within some cultivars and management systems, such as conventional and glufosinate-tolerant canola. Conversely, field violet can be controlled with registered POST herbicides in glyphosate- and imidazolinone-tolerant canola. These findings suggest that producers with field violet infestations may want to avoid selection of certain cultivars or, given the observed control with PRE glyphosate in the present study, may need to control the weed prior to crop sowing. Similar to results of research conducted in wheat, our findings in canola confirm that the activity of some herbicides is highly dependent on rainfall, soil moisture and the rate of weed growth. This was especially true for thifensulfuron methyl and glufosinate ammonium. The latter was found to confer only transient injury to field violet plants advanced beyond the 4-leaf stage, unless it was accompanied by rapid canopy closure, which negated recovery. Activity of POST glyphosate was also found to be dependent on environmental conditions, with rates of 222 and 445 g ae ha^{-1} providing control under good and poor growing conditions, respectively. This finding is important as it indicates that producers growing glyphosate-tolerant cultivars may be able to reduce their application rate when growing conditions are suitable and field violet is the dominant weed species.

Knowledge of the biology of field violet in Alberta provides information that can be integrated into management strategies for this weed. Information on the phenology and periodicity of emergence in spring wheat is useful because it indicates that emergence is unpredictable and thus timing of herbicide application should be based on the stage of weeds present during the critical period of crop establishment, and not on any particular calendar date. Observation of plant development within spring wheat suggests that seed production from this weed may begin early in the growing season and continue until the fall. Therefore, producers interesting in minimizing seedbank inputs may want to consider multiple herbicide applications, the first of which would be timed to target perennated winter annuals in May.

Experiments on the competitiveness of field violet revealed that the weed is unlikely to significantly reduce crop yield, especially when other weeds are present and a competitive crop cultivar is sown. This information is particularly relevant because it indicates that producers should base management decisions on the whole weed spectrum, and not specifically on field violet. Research conducted on lifecycle and morphology contributes to our general knowledge of field violet and indicates that the population in Alberta may be unique from what has been previously described.

5.5 Suggestions for future and continued research

Through the course of this project, there have been a number of different offshoot and extension experiments suggested that may further advance our understanding of this weed:

1. Determine the influence of tillage regime on field violet density, seed production, biomass and general fitness. Research on field violet in eastern Canada and Europe has suggested that density is greater in tilled fields. However, infestations in Alberta appear to be limited to reduced-tillage fields. This experiment would identify if the population in Alberta is indeed unique with respect to the influence of tillage. Soil moisture probes, at different depths, could be used to investigate whether differences are a consequence of moisture.
2. Identify the field-distribution of field violet. Some weed species are located in distinct patches, others are predominately located in borders, and others are located randomly throughout a field or are distributed along windrows. By examining the patchiness of field violet, we could speculate as to how it is spreading and the likelihood of its overall abundance increasing within the province.
3. Investigate the effects of altered row spacings, seeding and fertilizer rates, and fertilizer placement, on field violet emergence, growth and reproduction. Wilson *et al.* (1995) studied the influence of winter wheat density on field violet, but no similar experiments have been conducted in spring cereals. This experiment might provide recommendations for alternative, non-herbicidal strategies for control of this weed.

4. Determine the maximum dispersal distance of field violet seed from capsules. At seed maturity, capsules of field violet open facing upwards and, as the three valves of the capsule dry, they squeeze inward, propelling seed into the air. This experiment could be conducted in the greenhouse using sticky strips placed at different distances from the source plant to determine the maximum distance, which could give an indication of the rate at which field violet is likely to spread annually.

5. Compare the DNA, cDNA and mRNA of field violet from Alberta with that of the European plants to determine homology between populations. We observed some phenotypic differences between plants from Europe and those from Alberta, under an identical habitat. By conducting a genetic comparison it might be possible to determine if these differences are a reflection of a genetic shift in the population.

5.6 References

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Appendix A

Tables, figures and additional information for Chapter 1

A.1 Figures for Appendix A

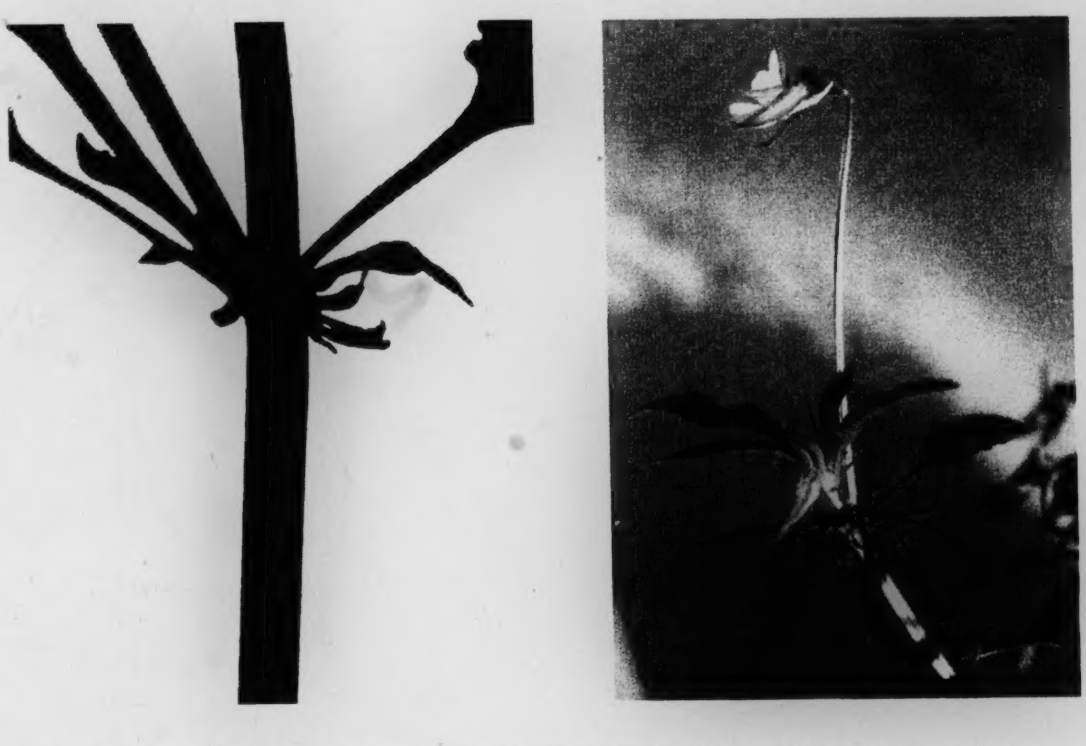


Figure A.1.1 Stipulate flowering axil of field violet showing the angular-terete stem, relative stipule size, upper leaf morphology and narrow pedicels.

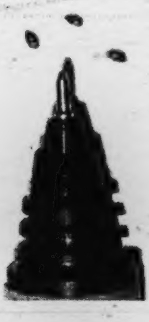
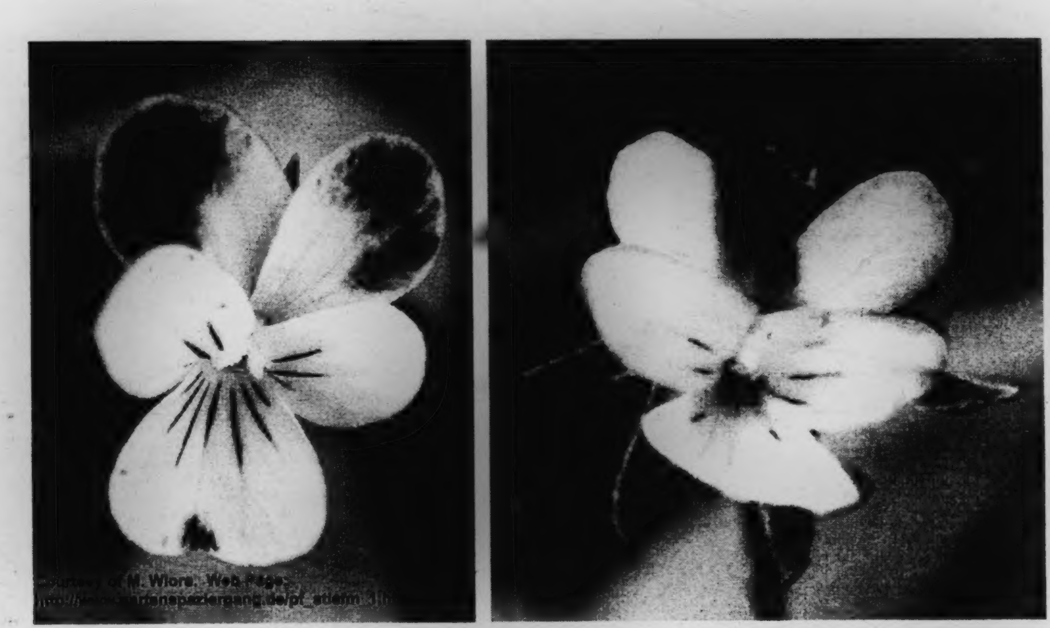


Figure A.1.2 Seed of field violet and a pen tip to allow for a comparison of size.



Courtesy of M. Wiora, Web Page,
http://[illegible]spaziergang.de/pf_stiefm[illegible]

Figure A.1.3 Flowers of *Viola tricolor* (left) and *Viola arvensis* (right) showing the difference in the sepal to petal length ratio between the species, a key diagnostic feature.

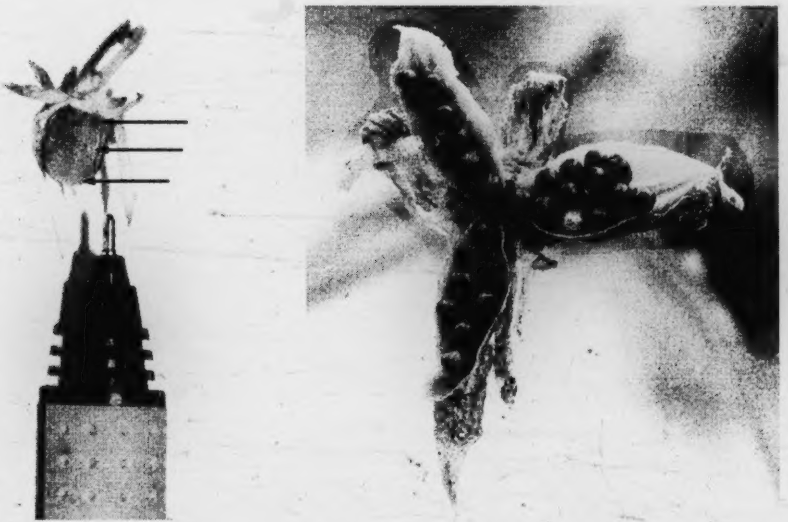


Figure A.1.4 Seed capsules of field violet. The picture on the left shows a mature, non-dehisced seed capsule with the top, middle and bottom arrows indicating the posterior, central and anterior positions, respectively, of a dehiscence fissure. The picture on the right shows the three valves of a dehisced seed capsule. As the valves dry, they fold inward propelling seed into the air.

Appendix B

Tables, figures and additional information for Chapter 2

B.1 Abstract for Chapter 2

The agrestal field violet (*Viola arvensis* Murr.), a pervasive weed in Europe, has been identified in reduced-tillage cereal fields in Alberta. The efficacy of registered, pre- and postemergence herbicides in spring wheat was assessed on natural infestations of the weed in the Aspen Parkland ecoregion of Alberta. Experiments were conducted at two locations in 2002 and 2003, and included a total of ten postemergence (POST) and two preemergence (PRE) herbicides. Herbicide activity was also evaluated in a greenhouse dose response assay. Only fluroxypyr + 2,4-D (107 + 557 g ai ha^{-1}), applied POST, provided control of field violet in 2002 when rainfall was limiting during the four week period prior to application. This herbicide reduced biomass 5 weeks after treatment (WAT) and plant density 8 WAT by 59 and 91%, respectively, relative to untreated controls. POST application of the Group 2 herbicides metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl only suppressed weed growth in 2002, but controlled the weed in 2003 when rainfall was greater, reducing plant density by 82–92% and rendering remaining plants effectively sterile. Suppression was also observed with MCPA + mecoprop + dicamba in 2002 and 2003, and with metribuzin only in 2003. PRE application of glyphosate (445 g ae ha^{-1}) and glyphosate + florasulam (450 + 5 g ai ha^{-1}) was evaluated only in 2003 and effectively controlled field violet throughout that growing season. Management of field violet is possible with herbicides registered for use on spring wheat in Alberta. However, the weed does not appear to cause significant crop production losses, hence herbicide selection should be based on knowledge of all species present within the weed flora.

B.2 Figures for Appendix B

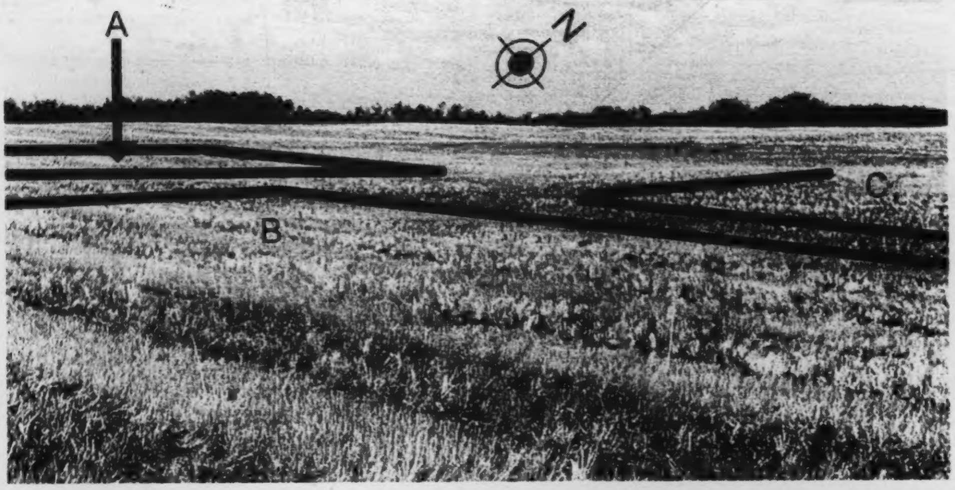


Figure B.2.1 Picture of the Lamont research site on June 10, 2002. Labels A and B refer to areas seeded to canola and wheat, respectively, and used to conduct herbicide management experiments on field violet. Label C was also seeded to wheat, and was the location of the experiments where the biology of field violet was investigated.

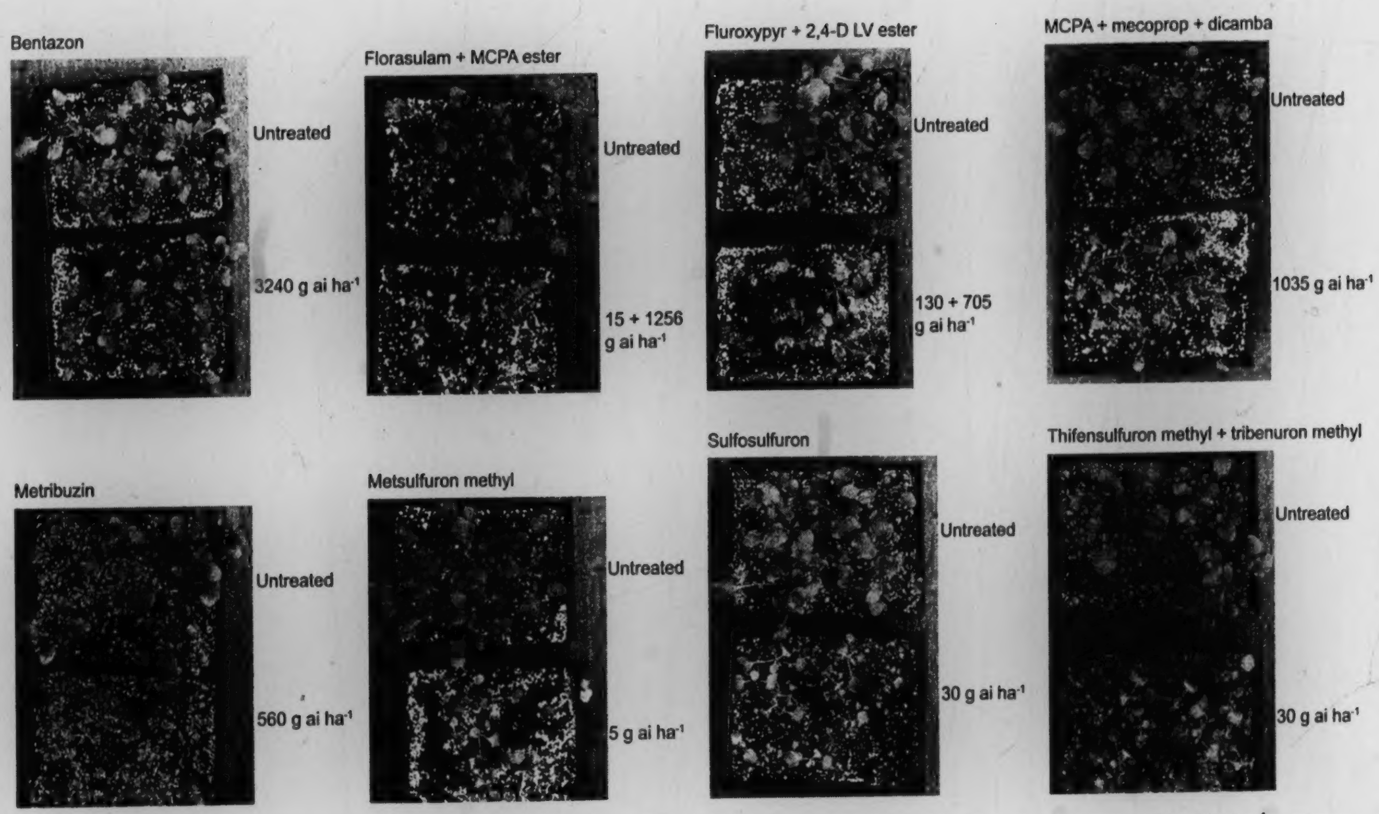

Bentazon
Untreated
3240 g ai ha-1
Florasulam + MCPA ester
Untreated
15 + 1256 g ai ha-1
Fluroxypyr + 2,4-D LV ester
Untreated
130 + 705 g ai ha-1
MCPA + mecoprop + dicamba
Untreated
1035 g ai ha-1
Metribuzin
Untreated
560 g ai ha-1
Metsulfuron methyl
Untreated
5 g ai ha-1
Sulfosulfuron
Untreated
30 g ai ha-1
Thifensulfuron methyl + tribenuron methyl
Untreated
30 g ai ha-1

Figure B.2.2 Field violet plants 10 days after application of herbicides in the greenhouse using a water volume of 200 L ha^{-1}. Shown are the untreated controls and the highest rate evaluated. Linuron is absent.

Appendix C

Tables, figures and additional information for Chapter 3

C.1 Abstract for Chapter 3

Field violet (*Viola arvensis* Murr.) is a winter or summer annual plant that is a serious weed of canola crops in Europe. The plant is becoming increasingly abundant within reduced tillage fields in Alberta, where its response to registered herbicides has not been evaluated. Two commercial fields within the Aspen Parkland ecoregion of Alberta were used to evaluate the efficacy of postemergencee (POST) herbicides against field violet in conventional, imidazolinone-tolerant and glufosinate-tolerant canola cultivars, as well as to evaluate the weed's response to various timings and rates of glyphosate in glyphosate-tolerant canola. Herbicide activity was also evaluated in a greenhouse dose response assay. Control of field violet was less in field experiments conducted in 2002 than in 2003, possibly due to abnormally low rainfall in the former. No POST herbicides evaluated provided weed control in conventional canola. Glufosinate ammonium (500 g ai ha^{-1}) control was unacceptable unless the crop canopy closed shortly after application. In imidazolinone-tolerant canola, thifensulfuron-methyl reduced weed density (8 weeks after treatment (WAT)) and biomass (5 WAT) by 79 and 86% relative to untreated controls in 2003, but was less efficacious in 2002 when plants were not actively growing at the time of herbicide application. Imazamox + imazethapyr did not affect weed growth. Field violet was controlled by POST glyphosate at rates of 222 and 445 g ae ha^{-1} in 2002 and 2003, respectively, and by PRE glyphosate (445 g ae ha^{-1}) in both years. Post-harvest application of glyphosate provided good control throughout the following growing season when spring emergence was minimal. Strategies for effective herbicide management of field violet are dependent on cultivar selection and management system, but are improved by timing application to target young, actively growing plants.

C.2 Figures for Appendix C

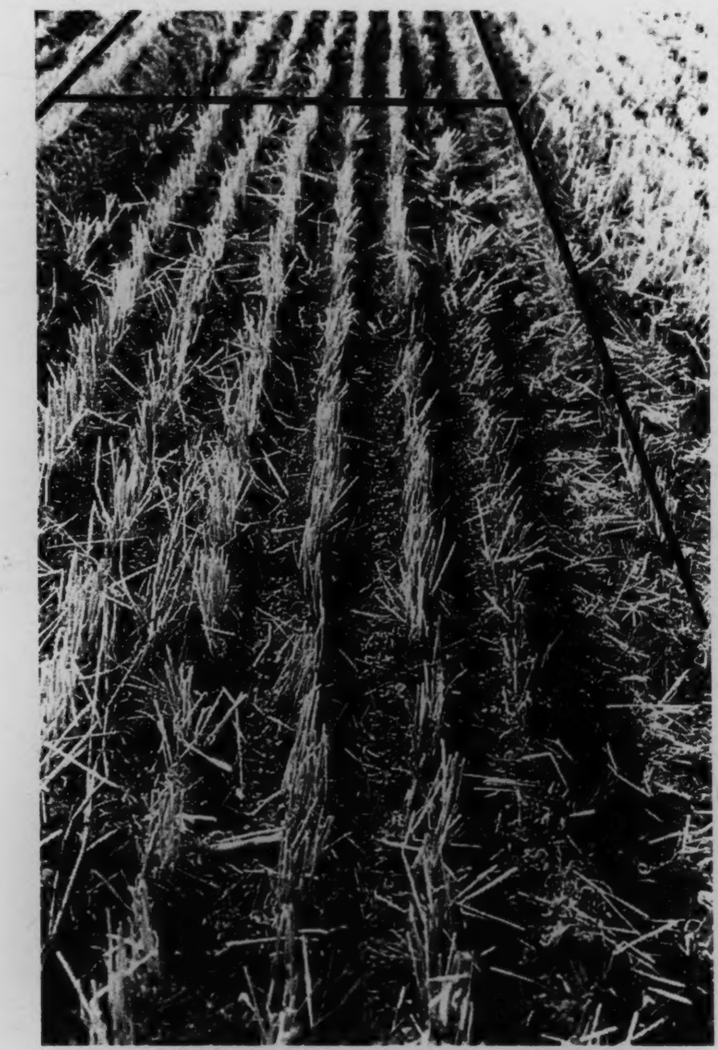
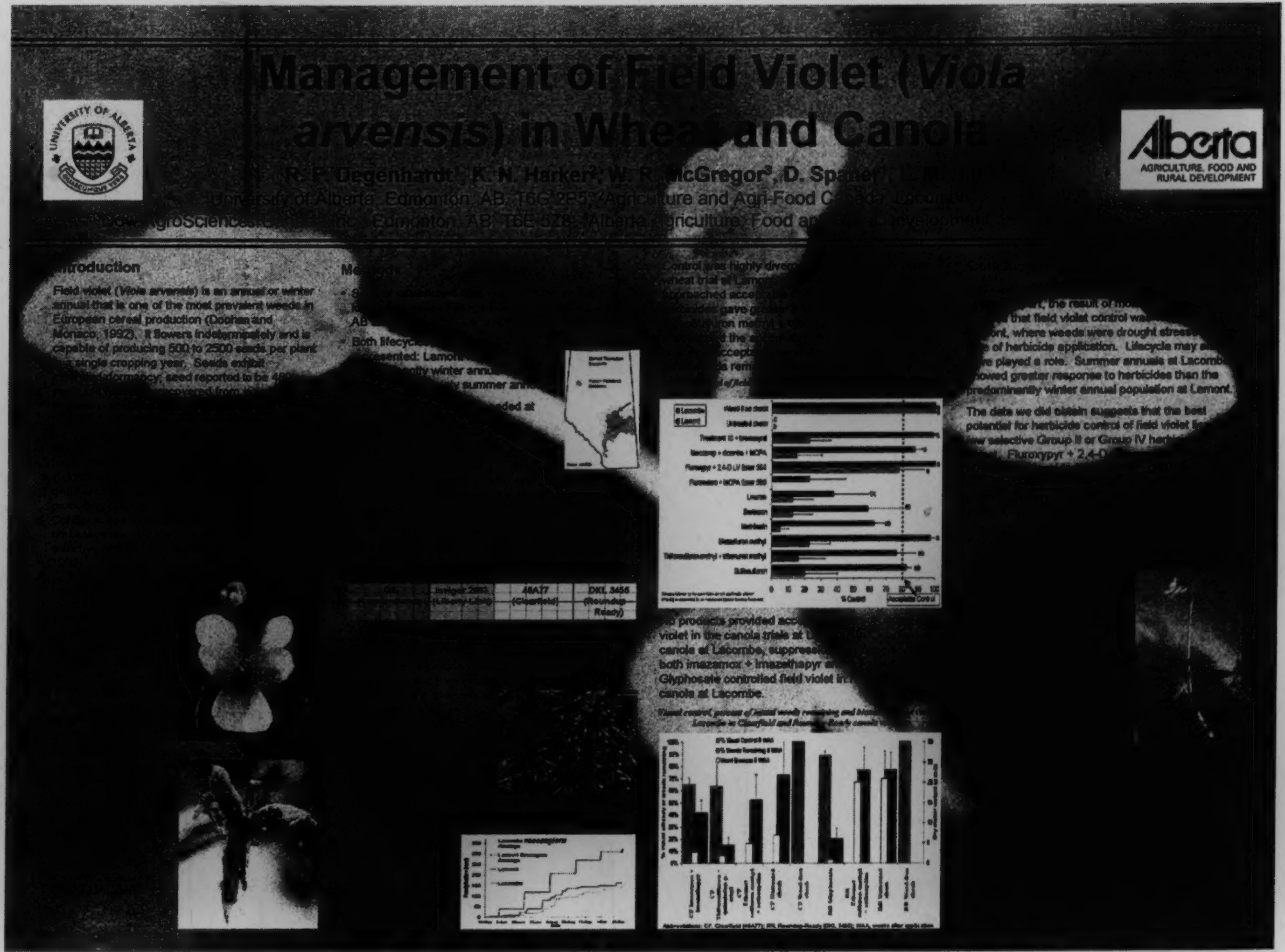


Figure C.2.1 Direct seeded plots in Lamont containing canola on June 11, 2002. Plots were 8.5 m long, 2 m wide and contained 6 crop rows, enclosed on both sides by a row of winter wheat.

Figure C.2.2 Field violet plants 10 days after treatment with clopyralid at 600 g ai ha^{-1} in the greenhouse. At this rate, growth was not impeded, but rather petioles appeared to grow longer and show slight epinasty.

Figure C.2.3 Field violet plants 4 days after treatment with glufosinate ammonium at 200 g ai ha^{-1} in the greenhouse. At this rate, the chlorosis and stunting observed was transient and plants recovered from injury by regrowing new leaves from axial buds.

C.3 Summary and extension information for Chapter 3



Management of Field Violet (*Viola arvensis*) in Whea[illegible] and Canola

R. P. Degenhardt[1], K. N. Harker[2], W. R. McGregor[3], D. Spaner[1] [illegible]

[1]University of Alberta, Edmonton, AB, T6G 2P5; [2]Agriculture and Agri-Food Canada, [illegible]

[3]Dow AgroSciences [illegible] Edmonton, AB, T6E 5Z8; [4]Alberta Agriculture, Food an[illegible] Development [illegible]

Introduction

Field violet (*Viola arvensis*) is an annual or winter annual that is one of the most prevalent weeds in European cereal production (Doohan and Monaco, 1992). It flowers indeterminately and is capable of producing 500 to 2500 seeds per plant [illegible] single cropping year. Seeds exhibit [illegible] dormancy; seed reported to be 4[illegible] [illegible] recovered from [illegible]

Me[illegible]

- S[illegible]
- Both lifecycle[illegible] [illegible]esented: Lamon[illegible] [illegible] winter annu[illegible] [illegible] summer ann[illegible] [illegible]eded at

Control was highly diver[illegible] wheat trial at Lamon[illegible] [illegible]pproached accep[illegible] [illegible] gave g[illegible] [illegible]ron meth[illegible] [illegible] the a[illegible] [illegible] accept[illegible] [illegible] rem[illegible]

[illegible]	Invigor 2663 (Liberty Link)	46A77 (Clearfield)	DKL 3456 (Roundup Ready)

[illegible] products provided acc[illegible] violet in the canola trials at [illegible] canola at Lacombe, suppressi[illegible] both imazamox + imazethapyr a[illegible] Glyphosate controlled field violet in [illegible] canola at Lacombe.

[illegible], the result of mo[illegible] [illegible] that field violet control wa[illegible] [illegible]ont, where weeds were drought stress[illegible] [illegible] of herbicide application. Lifecycle may a[illegible] [illegible] played a role. Summer annuals at Lacomb[illegible] [illegible]owed greater response to herbicides than the predominantly winter annual population at Lamont.

The data we did obtain suggests that the best potential for herbicide control of field violet li[illegible] [illegible] selective Group II or Group IV herb[illegible] [illegible] Fluroxypyr + 2,4-D [illegible]

Control of field violet (*Viola arvensis*) in wheat and canola crops in Alberta with pre- and postemergence herbicides

R. F. Degenhardt[1], D. Spaner[1], K. N. Harker[2], W. R. McGregor[3], L. M. Hall[1,4]
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[3]Dow AgroSciences Canada Inc., Edmonton, AB.; [4]Alberta Agriculture, Food and Rural Development, Edmonton, AB.

Introduction

Field violet (*Viola arvensis* Murr.) is a winter or summer annual weed, ubiquitous in grain fields of Europe and increasing in abundance in North America (Doohan and Monaco 1992). It has recently been identified in reduced tillage fields of central Alberta. To date, there has been no research conducted on field violet in Alberta, and there are no herbicides registered for its control in the major crops of spring wheat and canola.

Objective

The purpose of this study was to evaluate the efficacy of pre- and postemergence herbicides on natural infestations of field violet in spring wheat and canola crops in Alberta.

Methods

- Experiments were conducted in 2002 and 2003 in two reduced-tillage fields with infestations of field violet within the Aspen Parkland ecoregion.
- A hard red spring wheat cultivar (AC Barrie), a conventional canola cultivar (Q2) and three herbicide-resistant canola cultivars (glufosinate tolerant, Invigor 2663; glyphosate-tolerant, DKL34-55; imidazolinone-tolerant, 45A77) were planted into adjacent experiments.
- Herbicides were applied when wheat plants were at the three- to five-leaf stage and canola plants were at the two- to five-leaf stage.
- Efficacy of herbicides on field violet was visually rated 4 and 8 weeks after treatment (WAT). Visual control was validated by quantitative assessments, including field violet plant density (surviving plants m^{-2}), reproductive potential (flowers plant^{-1}), and biomass (g dry matter m^{-2}).
- All experiments were designed as a randomized complete block, replicated four times. Each contained all herbicides and application timings being evaluated, as well as an untreated control.
- Results from each year were analyzed separately in mixed models with location and block effects considered random and herbicide effects considered fixed.

Results and Discussion

- Most herbicides were less effective in 2002 than in 2003, possibly because of abnormally low rainfall (Figure 1).
- In canola, glyphosate, applied PRE or POST, was the only herbicide that conferred control of field violet in 2002 and 2003. Both plant density and dry weight were reduced by as much as 97% relative to the untreated controls (Table 1).
- Application of thifensulfuron methyl to imidazolinone-tolerant canola reduced field violet plant density.
- Glufosinate ammonium had better activity in 2003 at both locations, conferring a high level of control at the Lamont location, where the glufosinate-tolerant canola cultivar was able to close the canopy shortly after application, and suppressing weed growth at the Lacombe location (data not shown).
- Field violet was fully tolerant of POST imazamox + imazethapyr, ethametsulfuron and clopyralid.
- In wheat, fluroxypyr + 2,4-D LV ester 600 was the only treatment that provided consistent control of field violet in both years of the experiment.

The Group 2 herbicides metsulfuron methyl, sulfosulfuron and thifensulfuron methyl + tribenuron methyl provided excellent control of field violet in 2003, but only suppressed weed growth in 2002.

- Metribuzin and MCPA + mecoprop + dicamba also suppressed weed growth in at least one year.
- PRE applications of glyphosate and glyphosate + florasulam were highly efficacious, significantly reducing weed density and reproductive potential relative to untreated controls.

Table 1. Response of field violet (*Viola arvensis*) to herbicides applied within wheat and canola in field experiments conducted at Lamont and Lacombe in 2002 and 2003

Treatment		Rate (g ai ha^{-1})	Visual Control (%) 2003	Visual Control (%) 2002	Plant density (No. m^{-2}) 2003	Plant density (No. m^{-2}) 2002	Reproductive potential (Flowers plant^{-1}) 2003	Reproductive potential (Flowers plant^{-1}) 2002
Clopyralid		**202**	**0**	**0**	**54**	**96**	**17**	**4**
Ethametsulfuron-methyl		**15**	**0**	**0**	**46**	**71**	**17**	**7**
Untreated control		**-**	**0**	**0**	**48**	**86**	**17**	**6**
	SE	**-**	**1**	**0**	**19**	**28**	**13**	**3**
Glufosinate ammonium		500	98	8	10 *	75	9	4
Untreated control		-	0	0	60	47	15	5
	SE	-	13	9	16	22	6	2
Imazamox + imazethapyr		15 + 15	12	33	40	65	15	4
Thifensulfuron methyl		15	96	32	10 *	51	1 *	2
Untreated control		-	0	0	47	65	12	5
	SE	-	4	17	13	20	4	2
Glyphosate		445	94	84	3 *	16 *	0 *	1 *
Glyphosate (PRE)		445	74	84	15	3 *	5 *	0 *
Untreated control		-	0	0	34	77	16	7
	SE		11	6	16	12	4	2
Bentazon		1075	0	26	27	27	12	4
Glyphosate (PRE)		445	93		13 *	-	2 *	
Glyphosate + florasulam (PRE)		445 + 5	88	-	1 *	-	1 *	-
Florasulam + MCPA Ester		5 + 416	0	11	40	30	13	3
Fluroxypyr + 2,4-D LV ester 600		107 + 357	23	19	7 *	3 *	2 *	[illegible]
Linuron		281	13	24	25	22	11	6
MCPA + mecoprop + dicamba		408 + 82 + 93	35	31	13 *	16 *	6 *	[illegible]
Metribuzin		219	93	24	14 *	27	7	2
Metsulfuron methyl		4	93	40	5 *	12 *	0 *	[illegible]
Sulfosulfuron		20	93	31	4 *	40	0	2
Thifensulfuron methyl + tribenuron methyl		10 + 5	11	46	2 *	36	1 *	[illegible]
Untreated control			0	0	43	39	13	5
	SE	-	7	12	19	12	2	1

[illegible]

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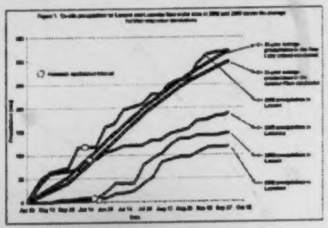
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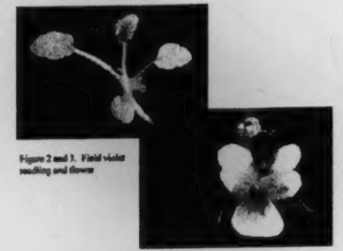
Figure 2 and 3. Field violet seedling and flower

Conclusions

Effective management strategies for field violet are cultivar-dependent. Growers of spring wheat, glyphosate- or imidazolinone-tolerant canola cultivars may be able to achieve agronomically acceptable control of field violet by applying an effective POST herbicide. In other systems, limiting interference and seed production from field violet may require a PRE application of glyphosate, where the weed can be targeted at its most susceptible stage of development.

Literature Cited

[illegible]

Appendix D

Tables, figures and additional information for Chapter 4

D.1 Abstract for Chapter 4

Field violet (*Viola arvensis* Murr.) is a weed of field crops in Europe and North America. To date, there has been no research conducted on its biology in Alberta, where farming practices and environmental conditions are unique from other regions where the weed is problematic. Naturalized infestations of field violet within two reduced-tillage fields in the Aspen Parkland ecoregion of Alberta were used to characterize the periodicity and phenology of field violet emergence and development, as well as to quantify its competitiveness with spring-planted wheat and canola in 2002 and 2003. Plants emerged intermittently throughout the growing season. Peaks of emergence were variable, although periods of peak emergence in early-June and September occurred in all experiments. Emergence was generally positively correlated with rainfall and negatively correlated with high temperatures. Spring annuals, competing with wheat, dispersed mature seed in as few as 7 weeks after emergence. Field violet rosettes were able to survive in a quiescent state for up to 19 weeks. Yield loss in wheat due to interference from field violet ranged from 4 to 7%. Losses in canola ranged from 0–6% of seed yield and 0–7% of crop biomass. Greenhouse experiments compared the morphology, phenology and fecundity of plants grown from seed originating in Alberta and the United Kingdom, and determined that the two populations were very similar, with the exception of the smaller corolla of Alberta-source plants that may reflect a shift towards autogamy. Seed production from domestic plants in the greenhouse was as high at 52,000 seeds per plant during a six month period. Field violet appears to be well adapted to growing conditions and farming practices within Alberta, but its poor competitive ability indicates that crop production losses can be avoided by employing cultural practices that improve crop competitiveness.

D.2 Figures for Appendix D

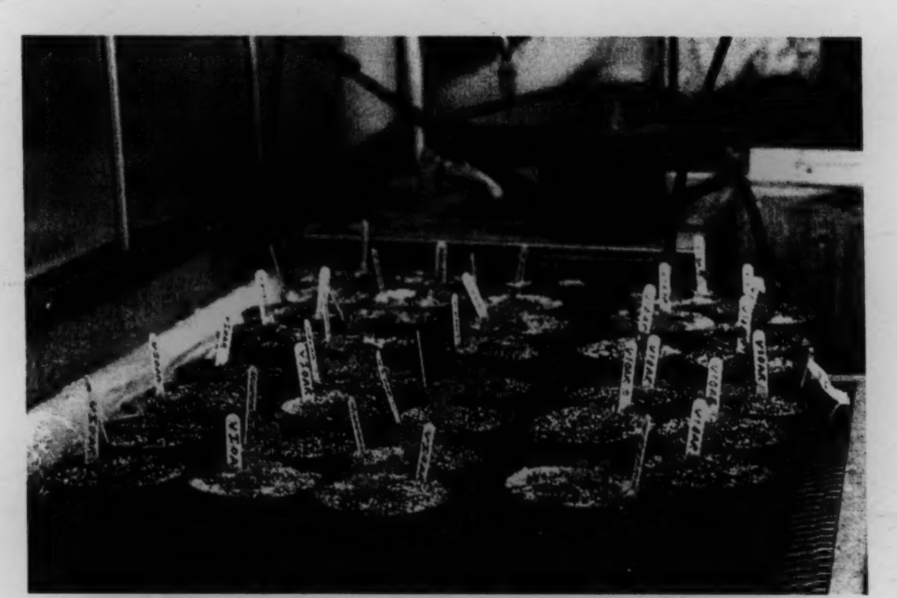

Figure D.2.1 Pots containing single field violet plants grown from Alberta- and European-source seed. These plants were used to investigate the morphology, development and reproductive potential of field violet in a greenhouse with a 16 hour photoperiod and 21 °C average temperature.

Figure D.2.2 Two quadrats of the Lamont emergence periodicity and phenology experiment, ten days after sowing wheat, on May 27, 2002. Quadrats are 1 m^2 in size and were protected by guard rows of spring wheat.

Figure D.2.3 Rosette stage field violet plant in the greenhouse, 32 days after planting, continuing to develop leaves from axial nodes. Stem extension in the greenhouse generally began 42–43 DAP.